Laser Sounder for Global Measurement of CO_2 Concentrations in the Troposphere from Space (a progress report)

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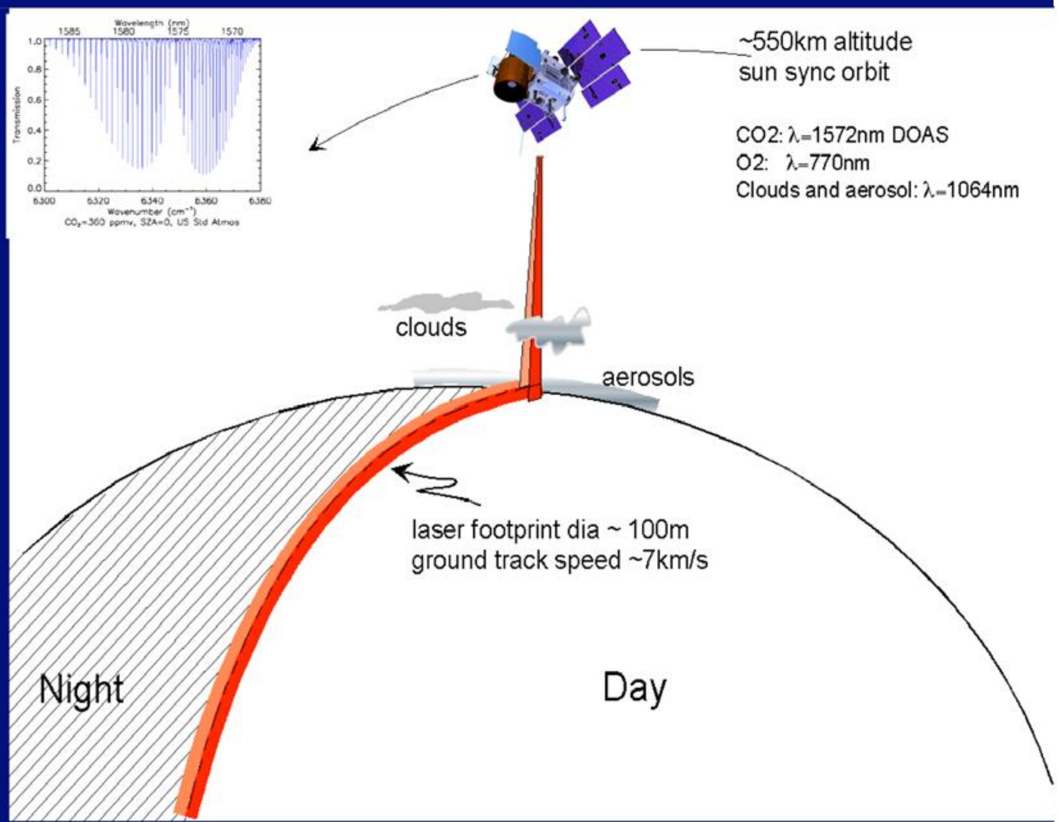
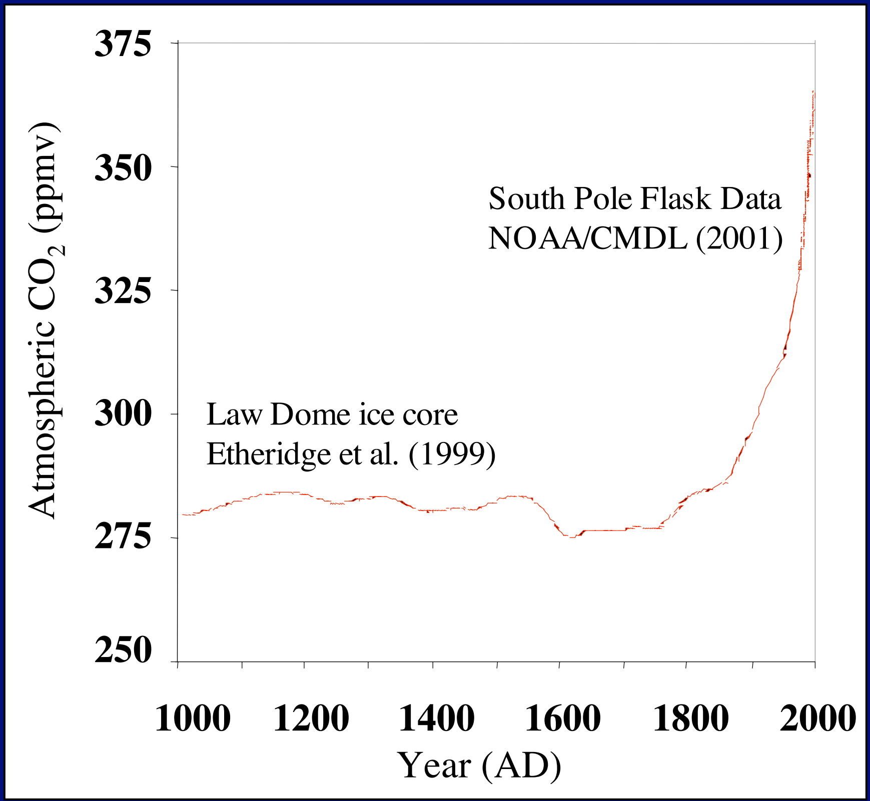
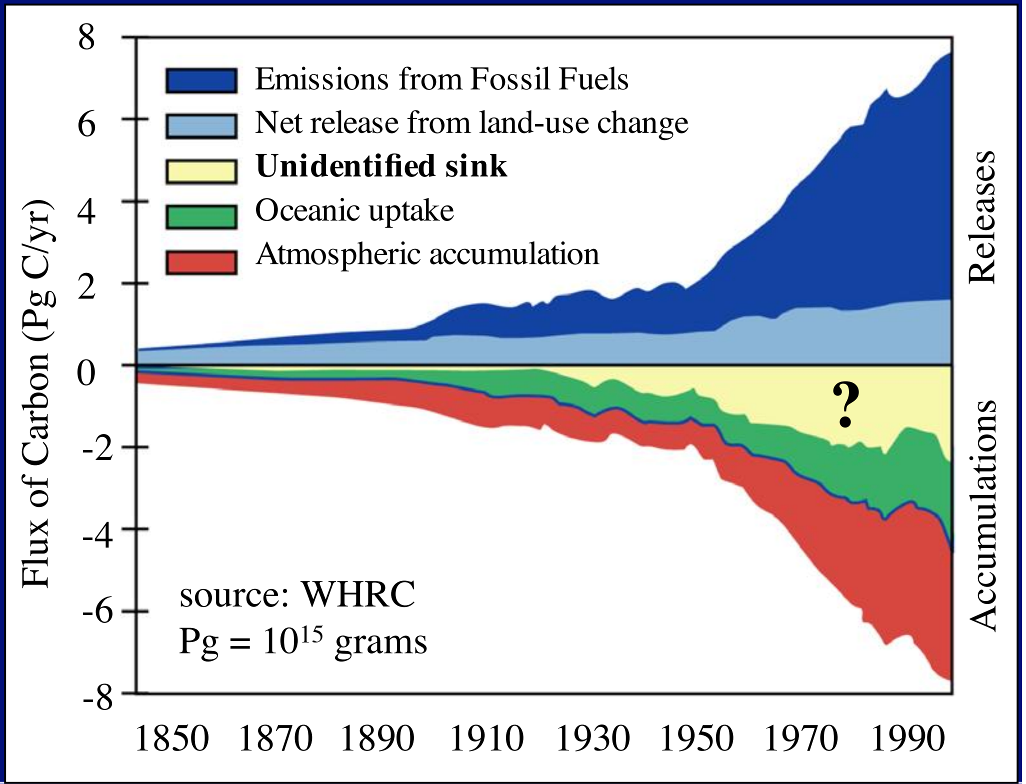


Atmospheric CO_2 - History

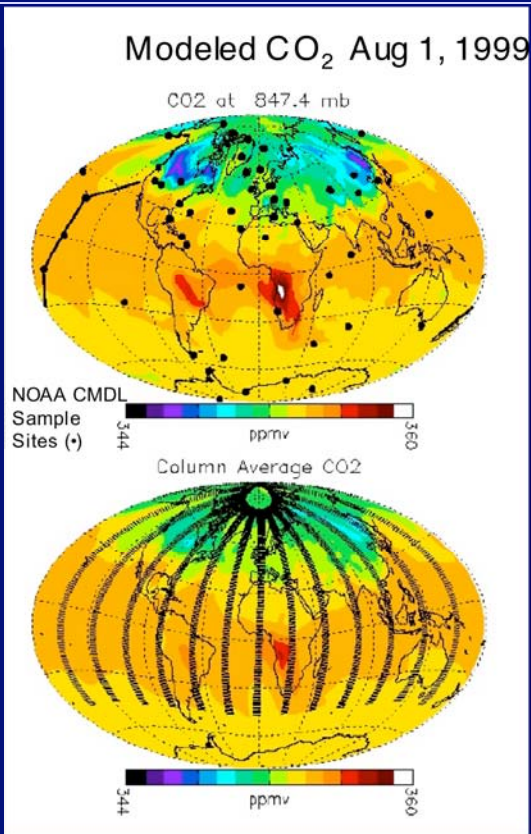


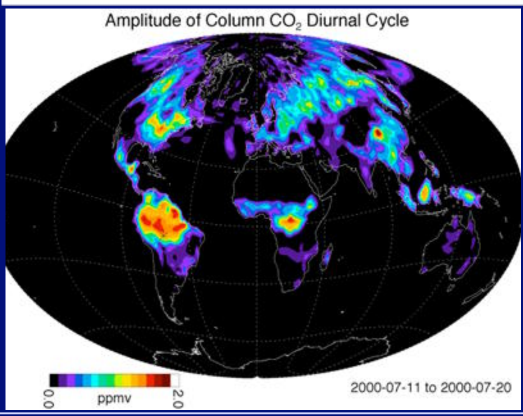
- Of anthropogenic CO_2 emitted to date, ~ 30% can not be accounted for - the "unknown sink"
- The "unknown sink" may be Northern Hemisphere forests.
- Will this sink continue to operate in the future?
- How will CO_2 fluxes in Arctic respond to warming ?



Atmospheric CO_2 is higher today than at any time in the past 400,000 years.

First orbital measurements will use sunlight & optical spectrometers





Global column measurements with much higher density & coverage than ground network

Characteristics:

- Measures entire absorption band
- Very high precision(<1%) needed
- Atmospheric scattering of sunlight from aerosols & thin clouds

Solar illum. Coverage:

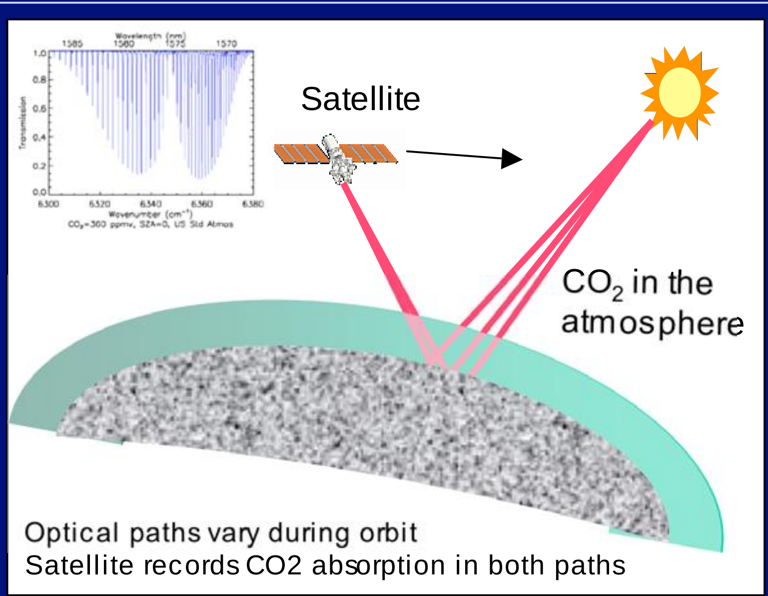
- Tracks shown for Nadir view & SZA < 65º
- Daytime only
- Errors from cloud & aerosol scattering
- Latitudes are limited by solar angle
  => high latt.'s only in local summer
- Glint areas over ocean - limited by geometry

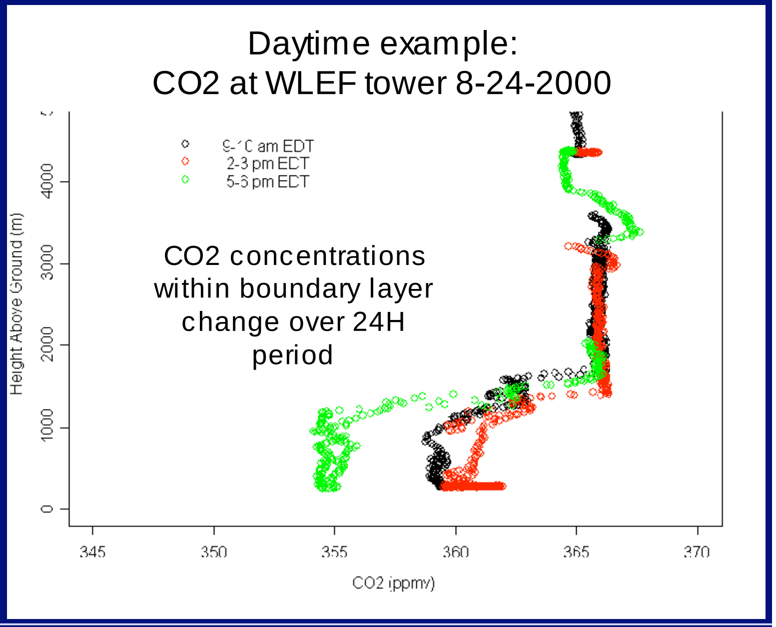
Diurnal variability

- Column varies by <2 ppm diurnally
- Within boundary layer, CO2 varies by > 10ppm (100 pm in MD in summer)

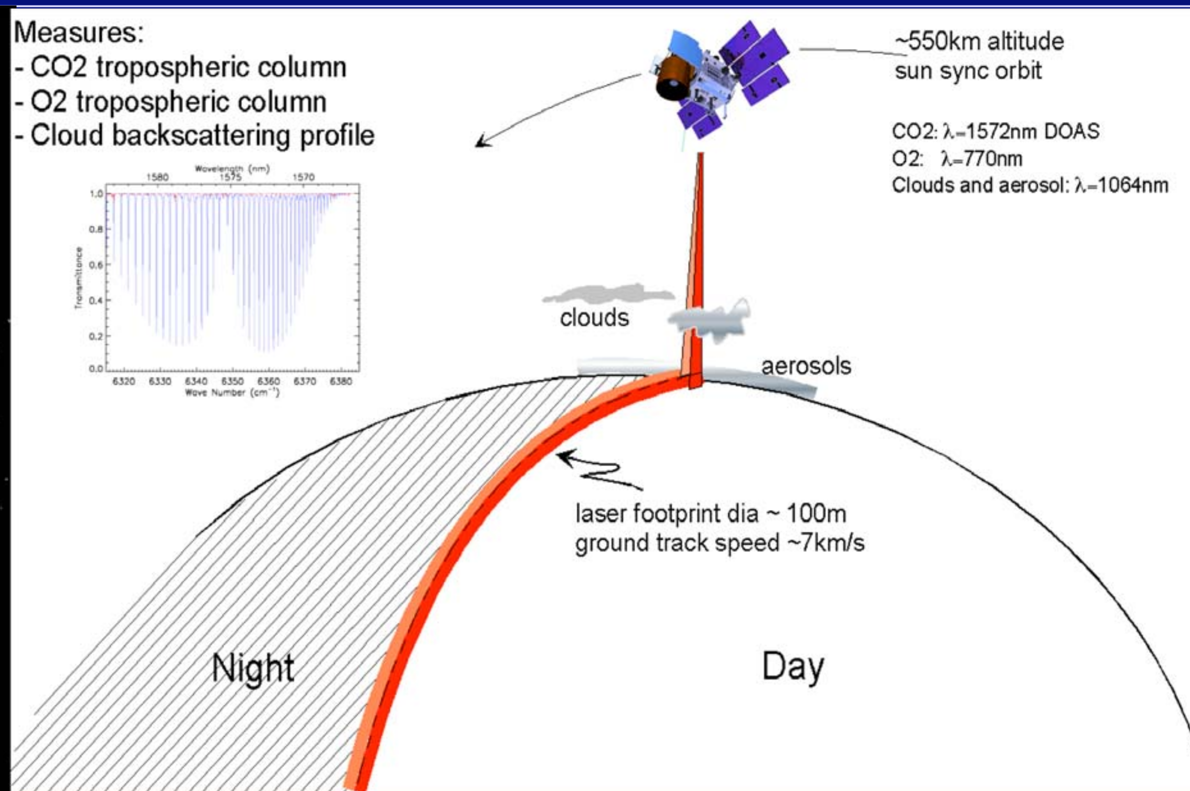
Not sampled:

- Co2 at low sun angles & nighttime
- Full ocean coverage
- Weighting of column to surface greatly enhances sensitivity to fluxes





Laser Sounder Approach



Why active (laser) measurements ?

- One nadir/zenith CO2 Column in measurement (illumination path=observation)
- Measures at night & at all times of day
- Measures at high latitudes
- Continuous measurements over oceans
- Smaller measurement footprint

- Improved detection of clouds
- Measures through broken clouds
- Measurements to cloud tops (known heights)
- Aerosol profiles allow best correction for scattering
- Potential for recovery of 2-3 altitude layers

Orbital Sampling of Dynamic CO2 concentrations

What is best orbit to sample the varying CO2 concentrations ?

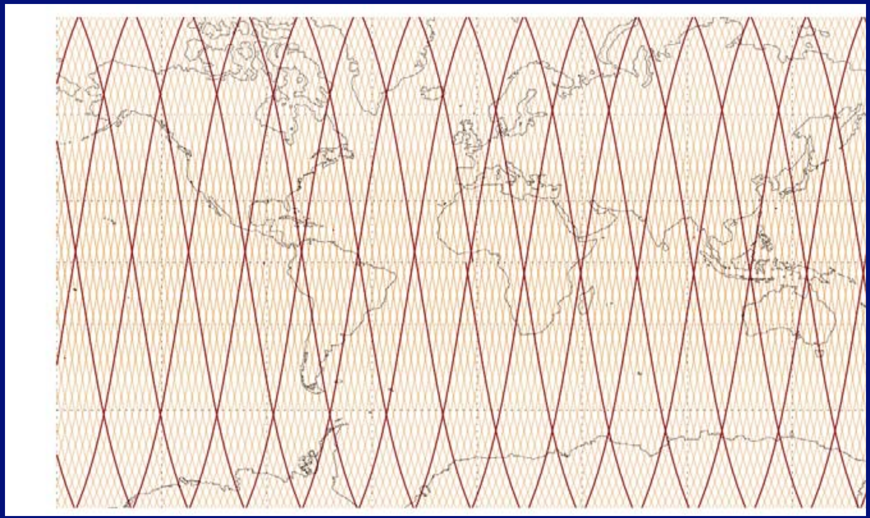
One example:

ICESAT orbit (ground tracks shown)

- 94 degree inclination
- ~ 600 km altitude
- 8-day repeat orbit shown
- For simulations - have aerosol backscatter profiles for four successive 8-day tracks

Red is ground tracks of one day out of the 8.

Orange plus red are tracks of entire 8-day coverage.



Another option:

- Dawn-dusk sun-sync orbit (~97 deg. inclination)

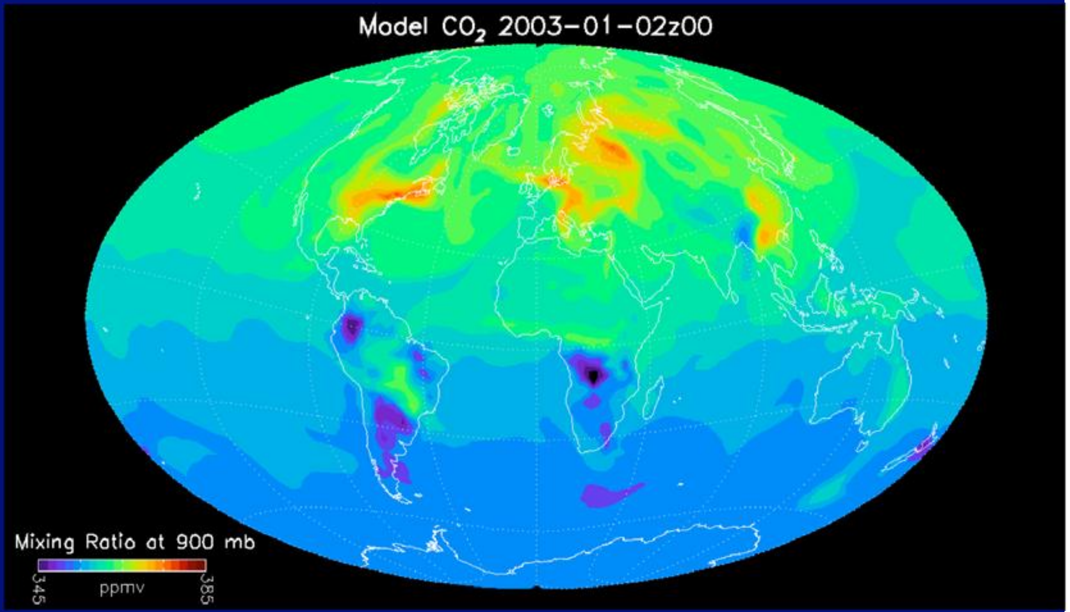
Global CO2 Concentration Simulation at 900 mbar pressure altitude

(Kawa et al., JGR, 2004)

The output step of the movie is 6 hrs, i.e., 4/day.

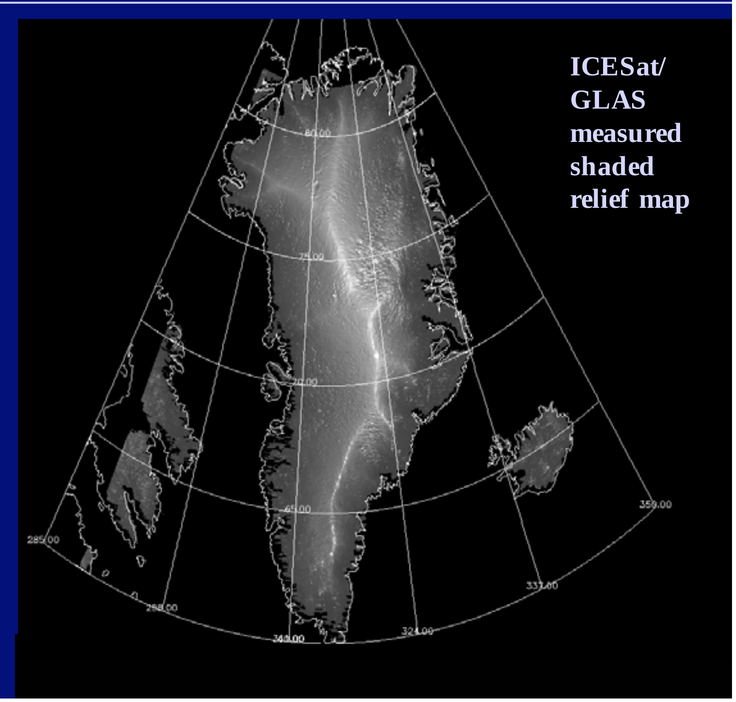
The Simulation runs on a 15-min time step.

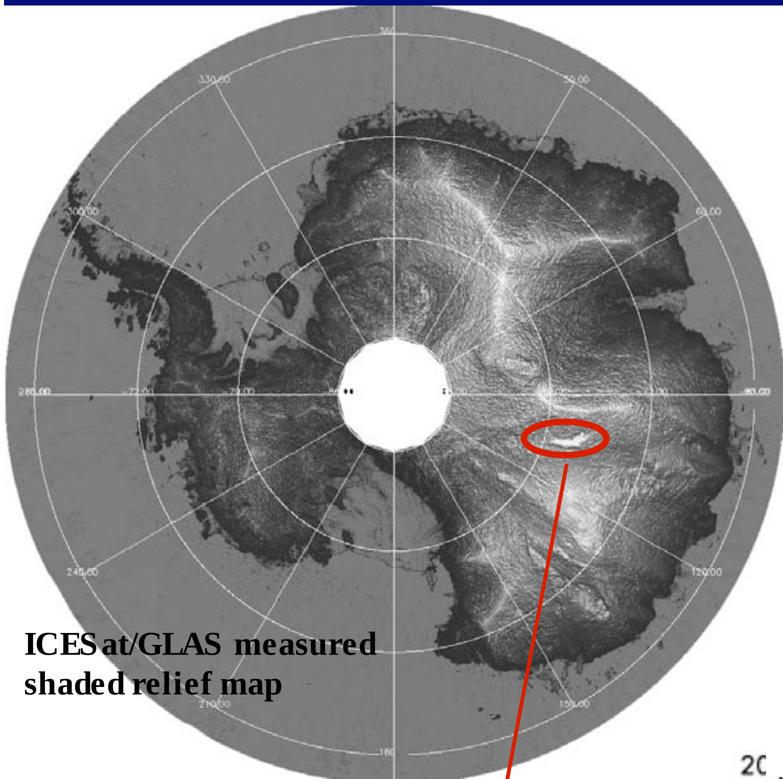
The movie run is similar to that except that the biological surface fluxes vary on an hourly time step.



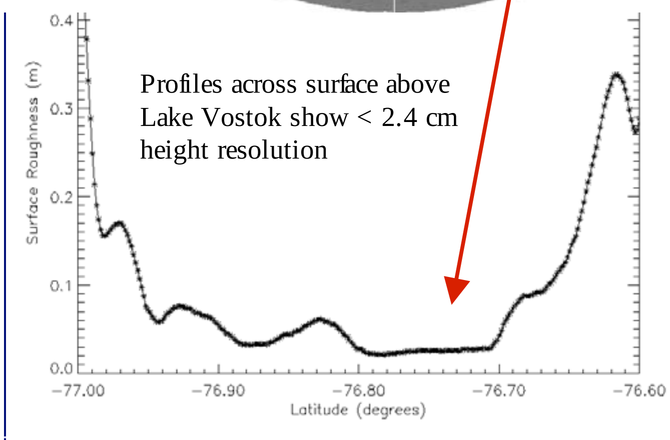
Geoscience Laser Altimeter System (GLAS) on the ICESat Mission

>1.3 Billion laser measurements of Earth's surface & atmosphere through 10 campaigns (so far)

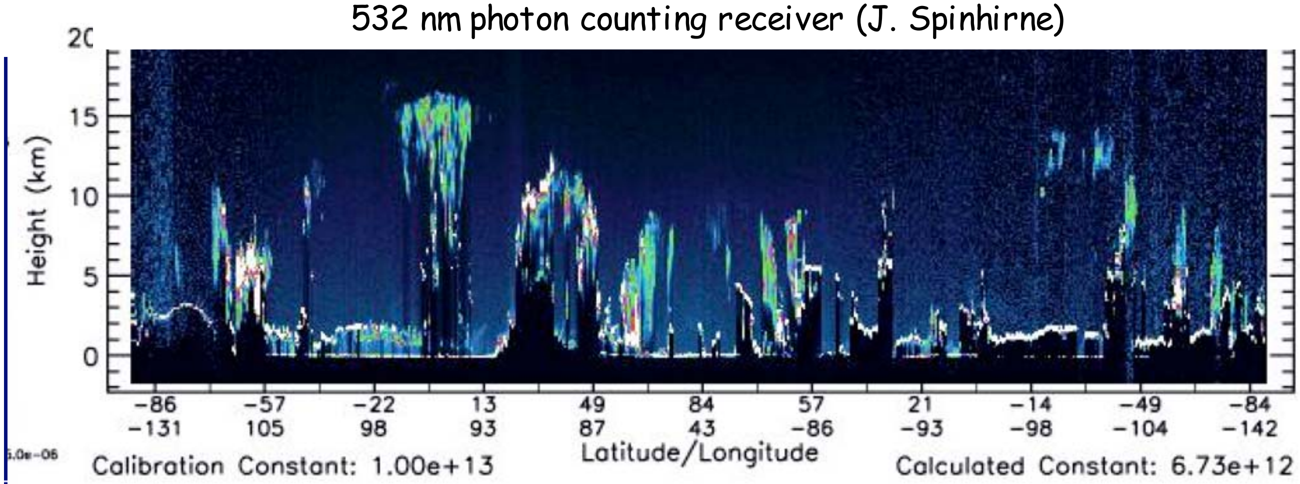




ICESat/GLAS measured shaded relief map

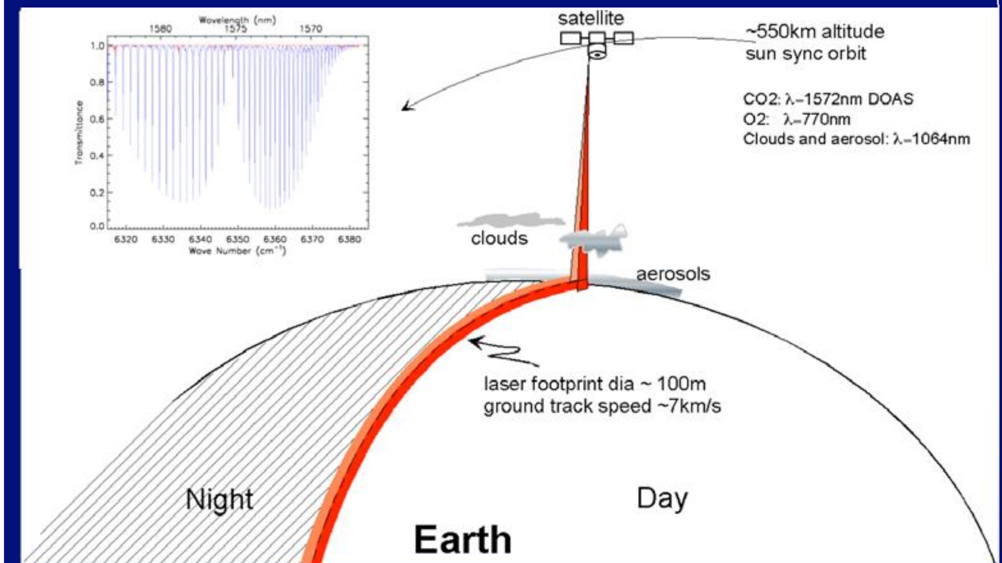


Atmospheric Backscatter Profiles (one orbit sample) measured by the GLAS 532 nm photon counting receiver (J. Spinhirne)



Laser Sounder for Global CO_2 Measurements: Airborne Demonstration, Science Measurements and Space Technology

(ESTO IIP program)



Objectives:

- Mission & instrument development
- Goal - monthly mapping of CO2 mixing ratio in lower troposphere at ~ 1 ppm
- Airborne instrument demo & space mission design study

Benefit:

- CO2 & O2 absorption - high resolution & stability
- Full global atmospheric sampling
- Measures day & night over all surfaces
- Improved CO2 determinations via measurements of clouds & aerosol scattering in path
- Resolves altitude distribution of CO2 into 2-3 layers

Approach:

- Use differential absorption on selected CO2 line.
- Echo signals are strong & laser is wavelength stable
- Leverages space-qualified EDFA laser technology
- Sensitive photon counting detectors
- High SNR measurements with 1 m GLAS telescope
- Follows ESTO ATI development - demonstrated remote laser measurements of CO2 diurnal cycle.

Milestones:

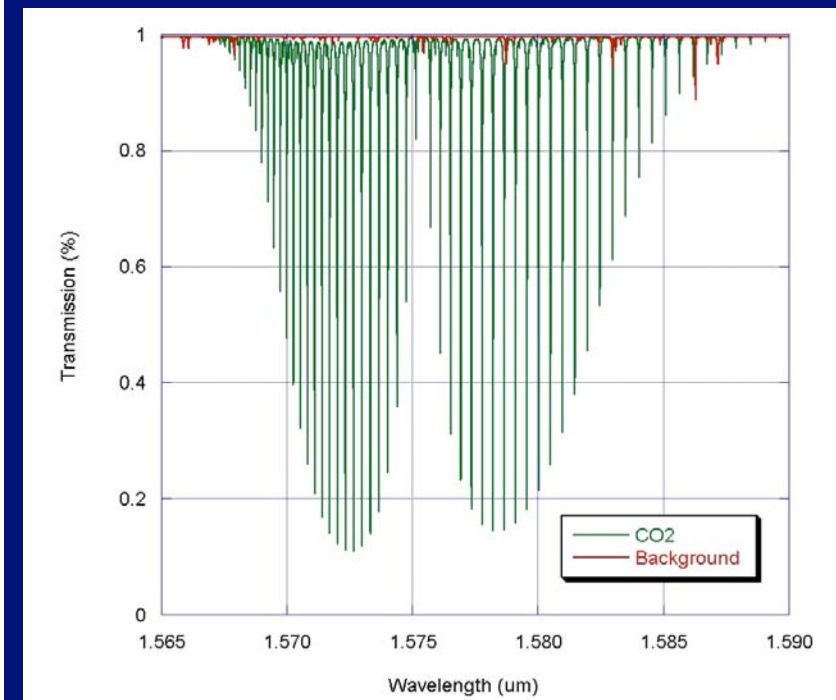
- 2006: Precise Ground-based day/night measurements of atmospheric CO2
- 2007: Field measurements of CO2 at tower site
- 2008: Precise airborne measurement demonstration

Applications:

- NASA Carbon Cycle - High-Resol. Atmos. CO2 - space
- NOAA-CMDL network (profiler)
- NASA OCO mission calibration-validation

CO_2 Band and Line Measurement Approach

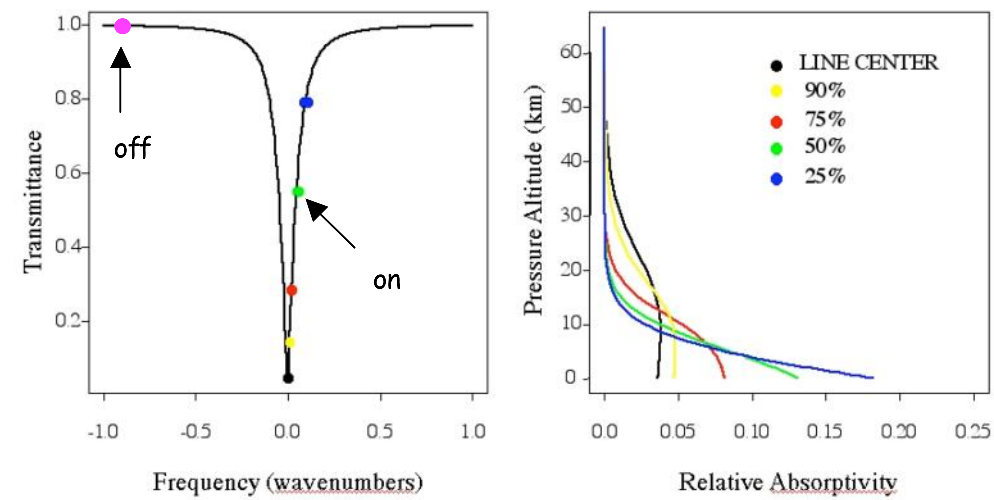
1570 nm CO2 Absorption Band from Space (HITRAN)



Column Measurement using laser tuned to sides of Absorption line provides Surface Weighted Measurement via CO_2 Line Broadening

Vertical sensitivity as a function of frequency for a line near 1570 nm:

Line centers more sensitive to high-altitudes (Doppler broadening dominates)
Line wings more sensitive to low-altitudes (Pressure broadening dominates)
CO_2 atmospheric concentration is biased to lower altitudes (molecular weight)



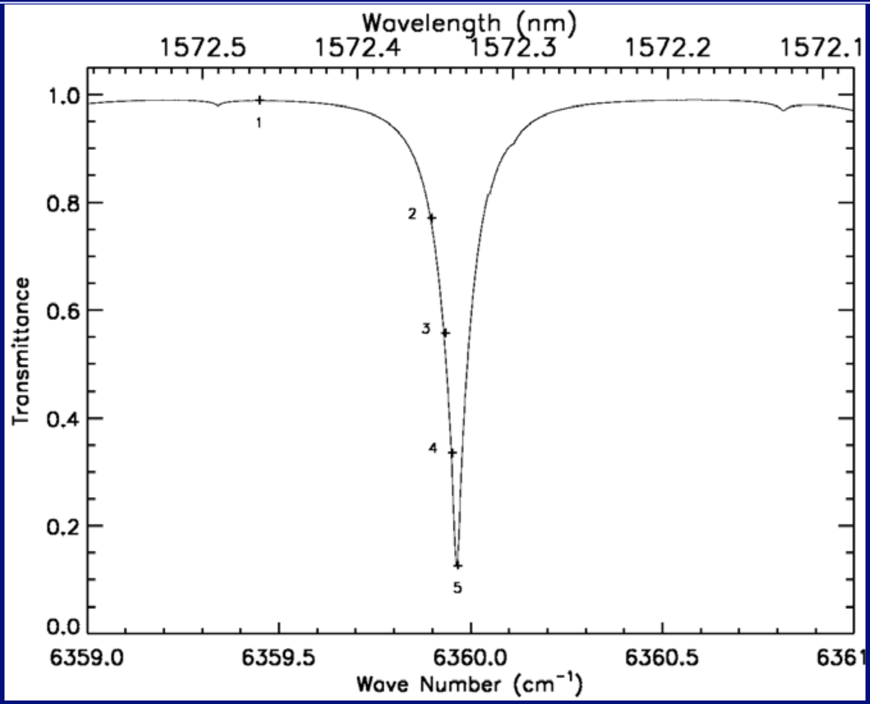
Resolution needed:

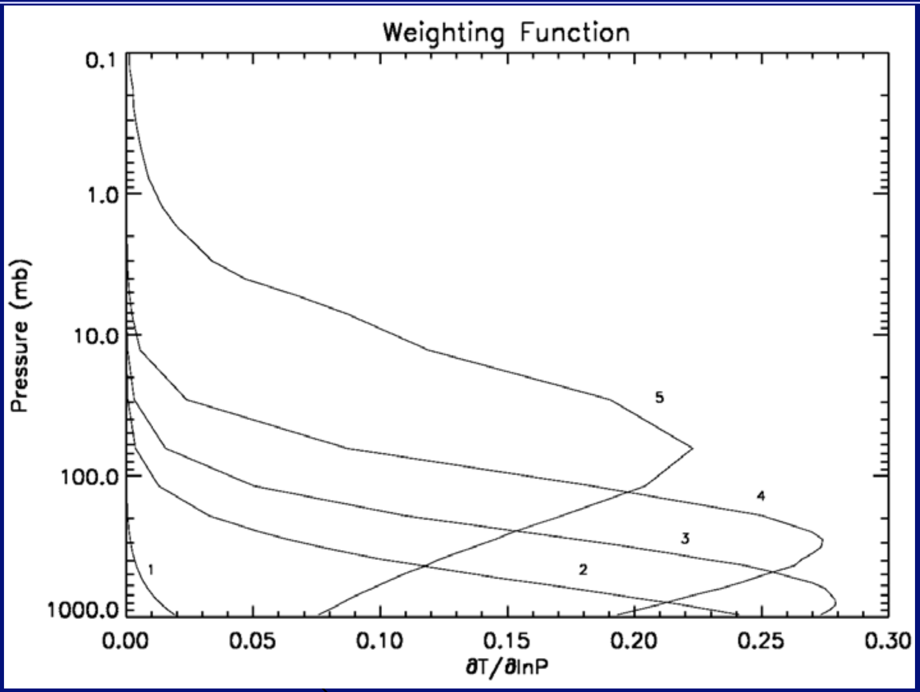
- ~ 0.1% in energy ratio (CO2 line absorption)
- Depends on line & position of "online" point
- Drives SNR of measurement & req'd stability

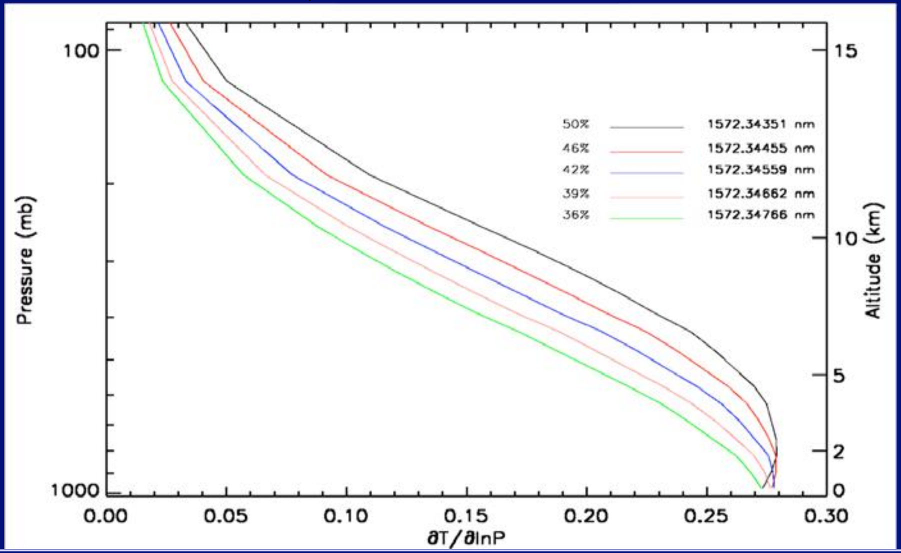
Laser provides:

- Very narrow typ. a few MHz (~0.1%) of line width (GHz)
- Very stable in wavelength
- On-line point is flexible; can be rapidly tuned on orbit

2. Simulation of CO_2 Line Measurement Approach







- Tune laser lines for optimum sensitivity

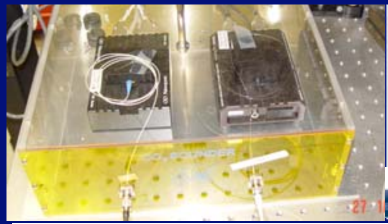
  - resolve stratosphere, troposphere partial columns

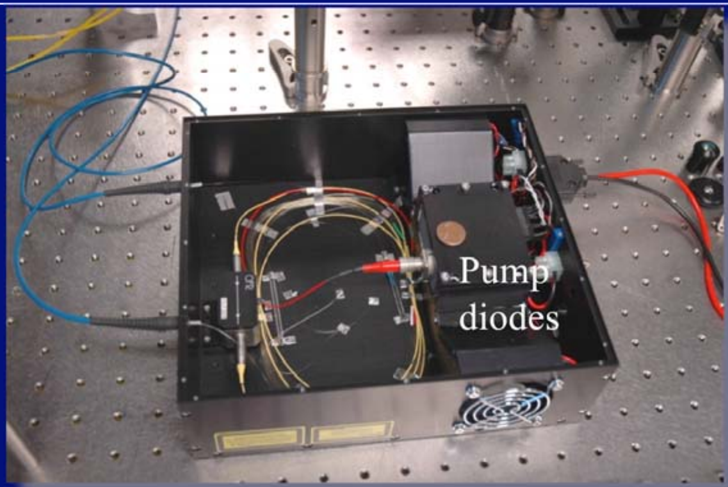
  - maximize sensitivity to planetary boundary layer CO_2 change

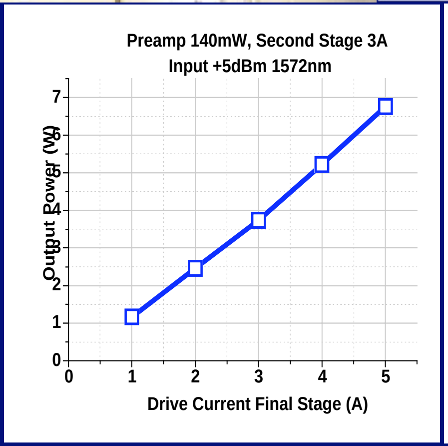
  - estimate impact of instrument errors

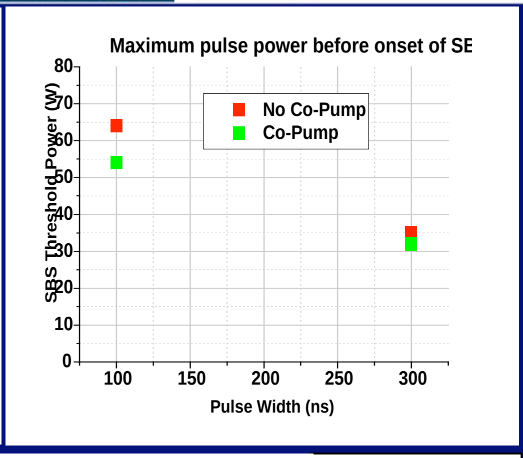
Diode Seed Lasers & Fiber amplifiers for CO_2 & O_2 channels

Tunable diode seed lasers



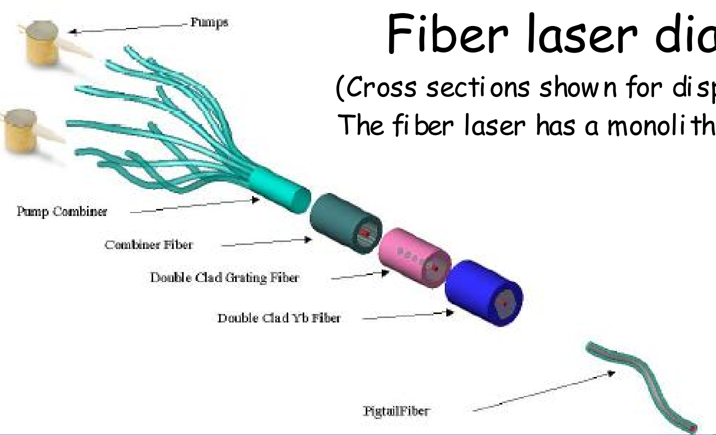






Fiber laser diagram

(Cross sections shown for display purposes. The fiber laser has a monolithic structure.)



Characteristics:

- Closed laser cavity - no contamination risk
- Fiber architecture - no misalignment risk
- Leverages B$'s of investment from industry
- Components built to Telcordia standards (can be even more stringent than space flight)
- Diode pumping technology is very reliable (undersea fiber optic repeaters)
- Distributed thermal load
- Electrical efficiencies > 15%
- Outside work in space flight development
- Wide availability of highly engineered parts
- Wavelength flexibility

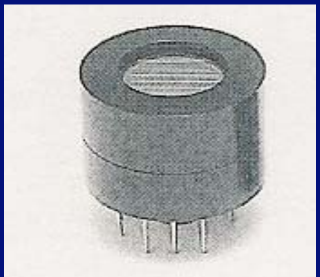
Co2 Sounding Channel - Photon counting Detectors

Hamamatsu H9170-75 PMT

-Detector currently used in breadboard receiver

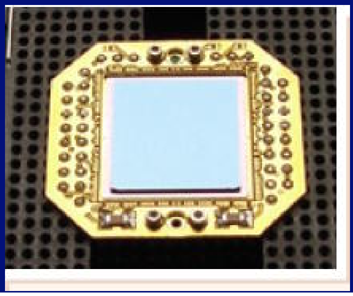
HV supply and PMT housing

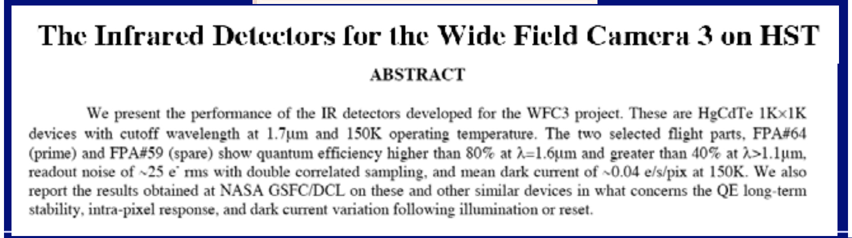
- Turn-key operation
- QE=2-3% (hand selected) at 1570nm
- InP/InGaAs photocathode
- Photocathode: ~5 mm diameter
- Dark count rate ~200 KHz at -80 C (TEC cooled)
- PMT power consumption ~150mW (can be cooled in space via TECs and radiators)



TO-8 PMT package with transmissive photocathode

1.0 - 5.0 micron Photon Counting Detector Candidate (from new Hubble WF cameras)

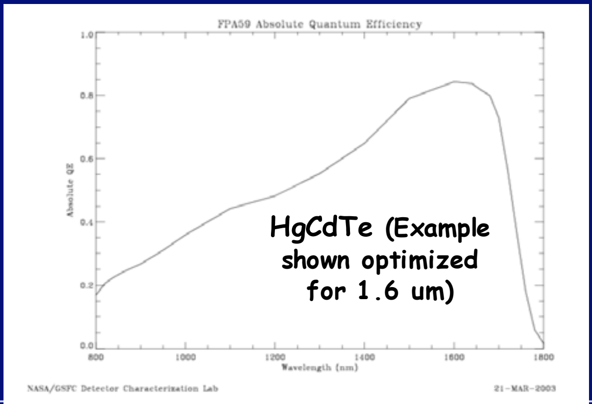




The Infrared Detectors for the Wide Field Camera 3 on HST

ABSTRACT

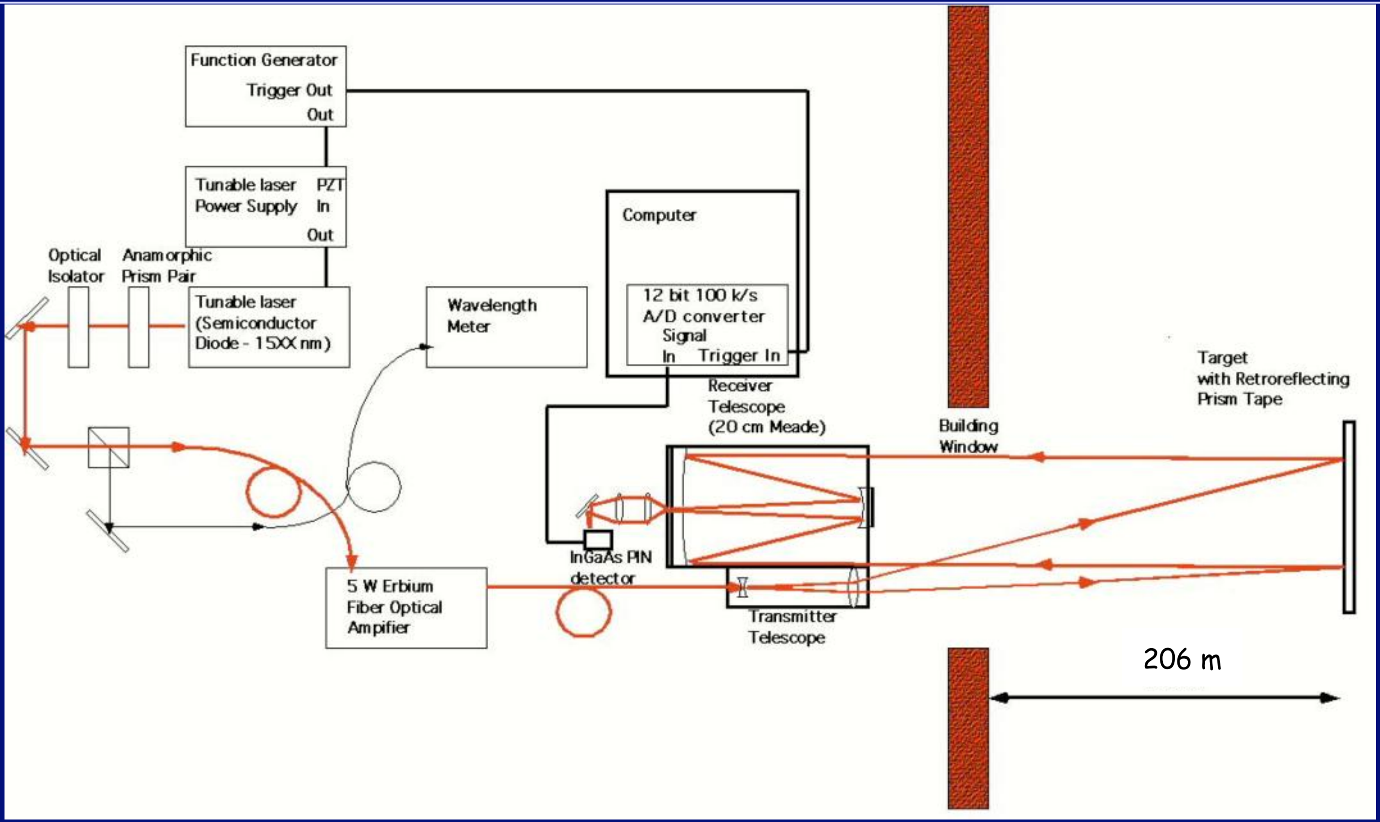
We present the performance of the IR detectors developed for the WFC3 project. These are HgCdTe 1K×1K devices with cutoff wavelength at 1.7μm and 150K operating temperature. The two selected flight parts, FPA#64 (prime) and FPA#59 (spare) show quantum efficiency higher than 80% at λ=1.6μm and greater than 40% at λ>1.1μm, readout noise of ~25 e⁻ rms with double correlated sampling, and mean dark current of ~0.04 e/s/pix at 150K. We also report the results obtained at NASA GSFC/DCL on these and other similar devices in what concerns the QE long-term stability, intra-pixel response, and dark current variation following illumination or reset.



80% photon detection/accumulation efficiency at 1550 nm with ~0.04 dark counts/sec at 150K

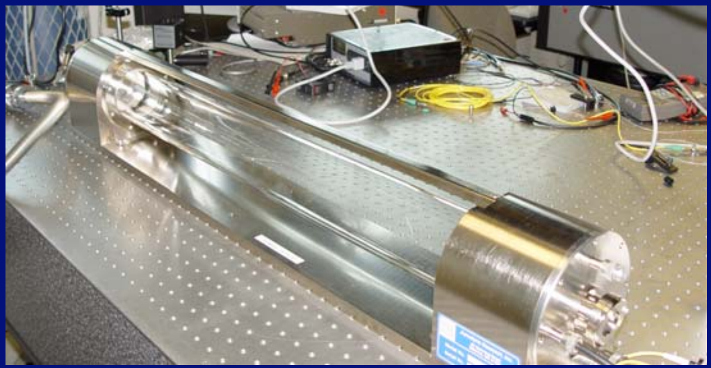
Present read-out configured for integrating applications

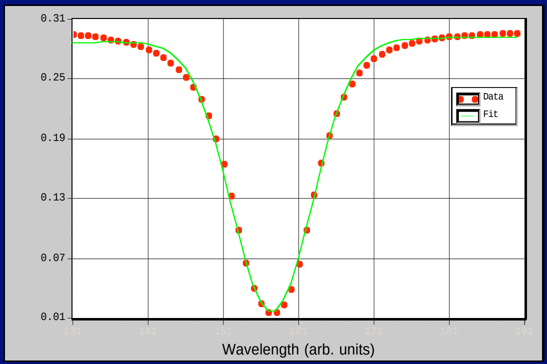
Breadboard CO_2 Laser Sounder; Gas cell & measurements



~ 300 m path length multi-pass absorption cell

- For system calibration
- Verify atmospheric CO2 measurements (300-400 ppm in air).
- 10 & 36 m cells used for line locking & calibration.



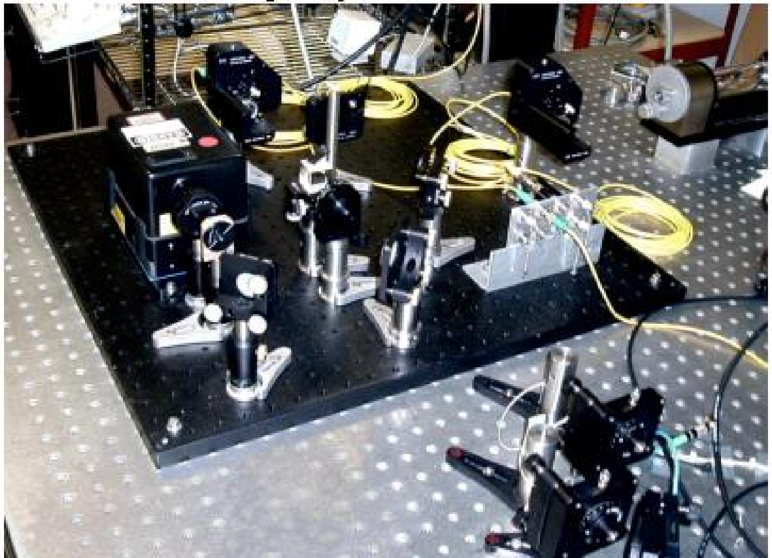


Sweep of CO2 absorption line with signal from fiber amplifier at low pressures (<6 mbar of CO_2) in the 36m cell

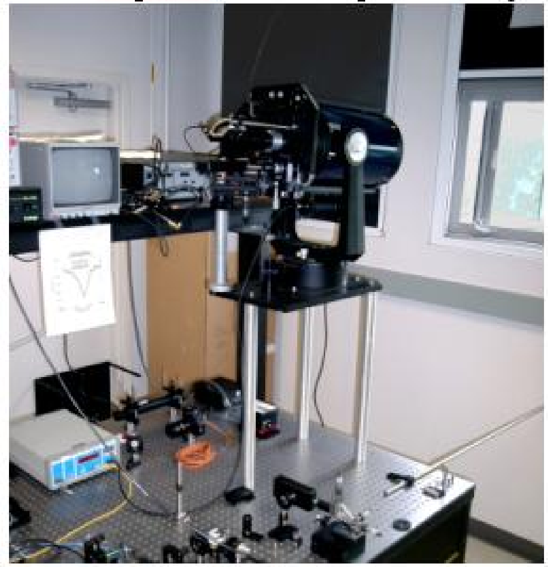
λ ~ 1571.111 nm , γ_D ~ 6.3 arb. units (0.36 GHz); ; P ~ 40 mW

Open Path Atmospheric CO2 Measurement
Test Range (206 m one way)

Frequency Tunable diode laser

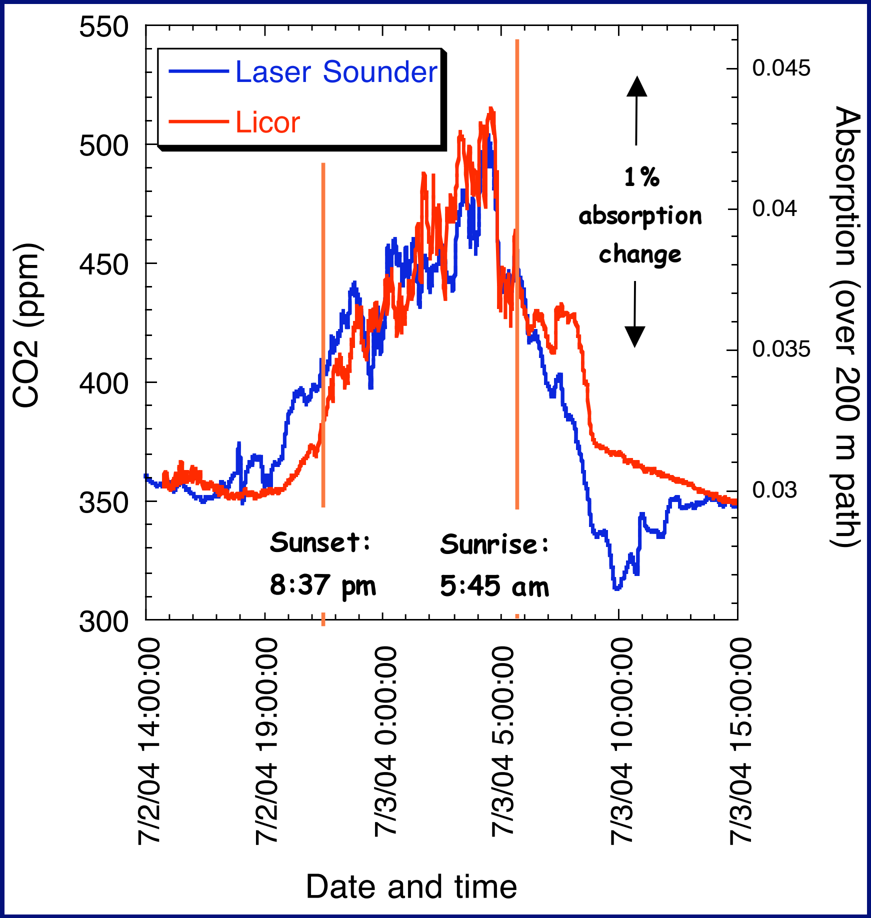


Fiber amplifer & Telescope assembly



Target (in tree)

Diurnal cycle of CO_2 measured over open path with Laser Sounder breadboard



Licor (in-situ samples):

- Single-point measurements from air intake on B33 rooftop
- Industry standard sensor

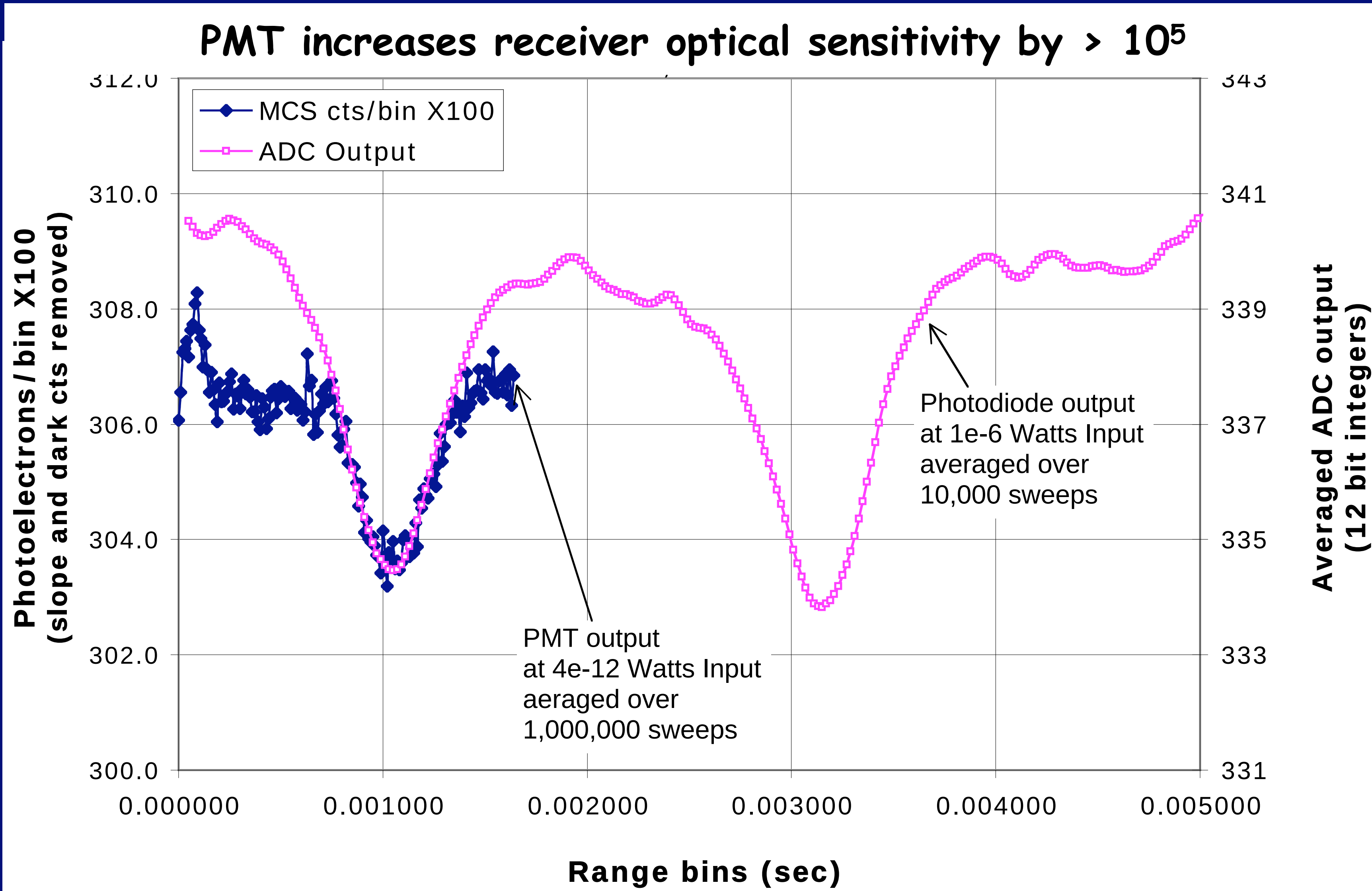
Laser Sounder:

- 206 m one-way open-path
- Data offset and scaled
- Not yet optimized

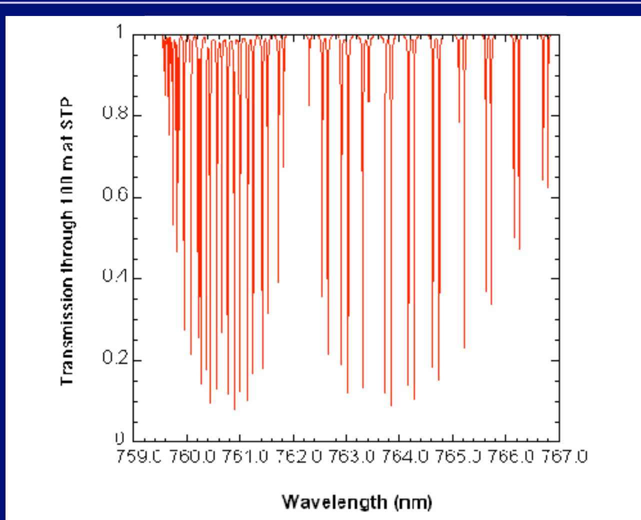
Results over 1st 16 hours:

- Agreement (stability) to 1 part in 500 in absorption
- Close to performance needed for space mission

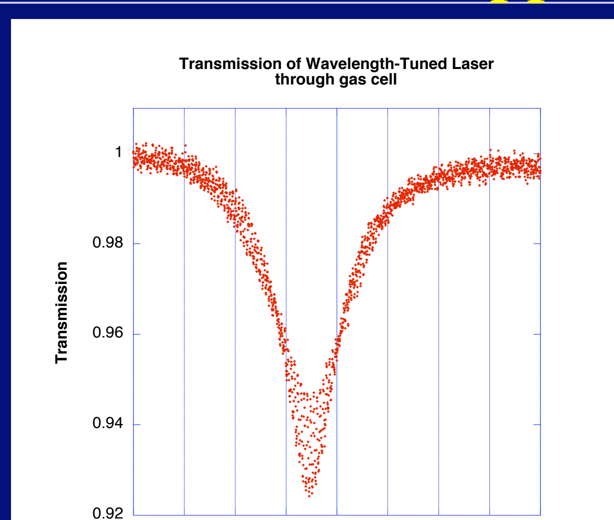
Open Path CO2 line measured with Frequency Swept diode source using Photon counting & Analog detectors

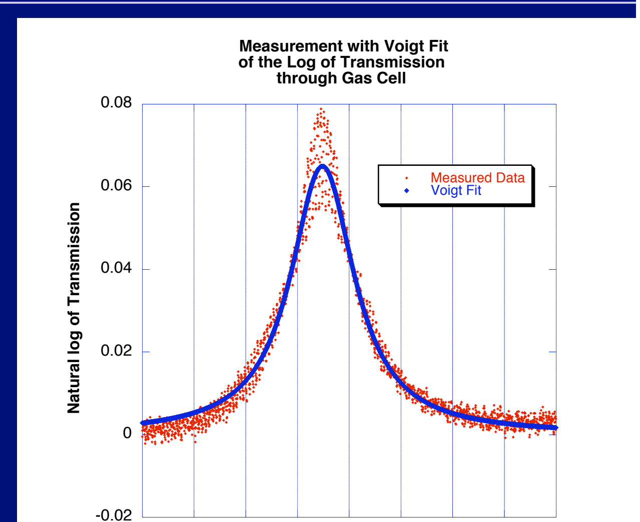


Oxygen (Reference) Channel & Laser Transmitter approach

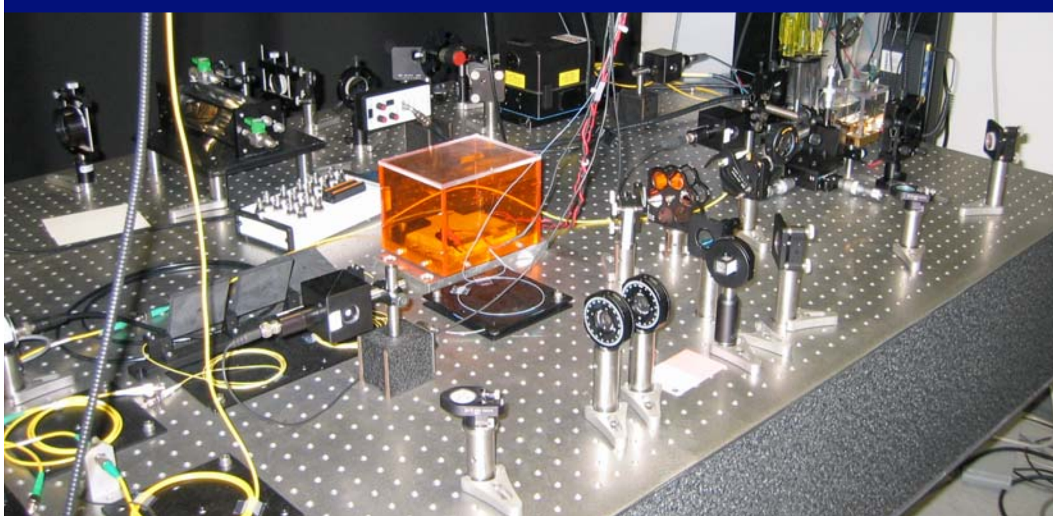


Oxygen A band: Calculated atmospheric transmission for 100 m path at STP





Some lab measurements of an O2 line : Wavelength (50 pm/div)
At 763.3 nm center wavelength



Laser Approach:

- Distributed Feed Back (DFB) Laser Diode seed laser
  ~1 MHz width, tunable, low-power, fiber coupled
- Erbium-Doped Fiber Amplifier (EDFA)
  - Single-mode, 10W peak power amplifier
- Frequency doubling crystal:
  - Periodically-Poled KTP
  - Expect > 50% Efficiency
- Tunable, stable, narrow frequency in 765 nm band
- Rugged, light-weight, efficient

Space Measurement Approach

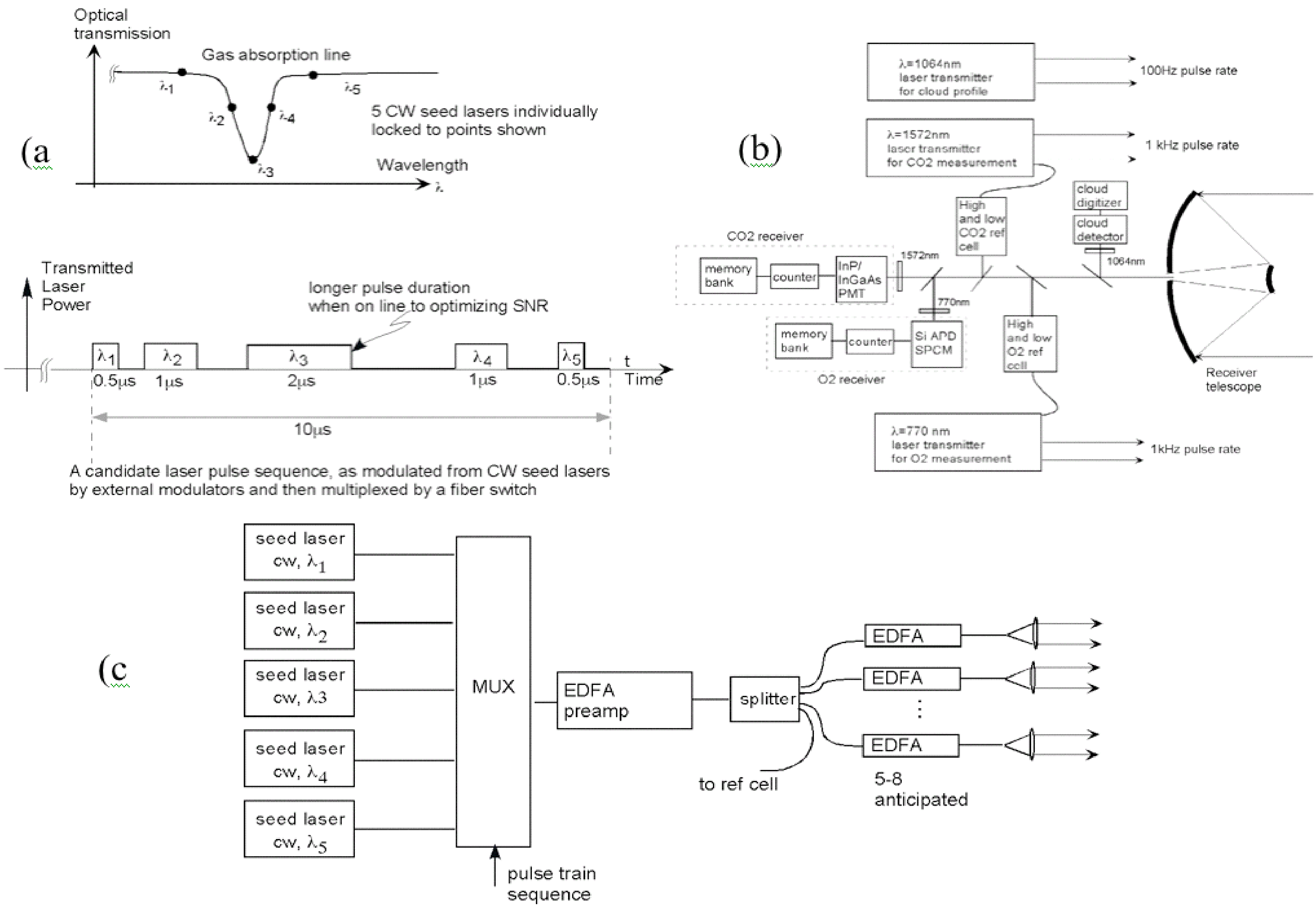
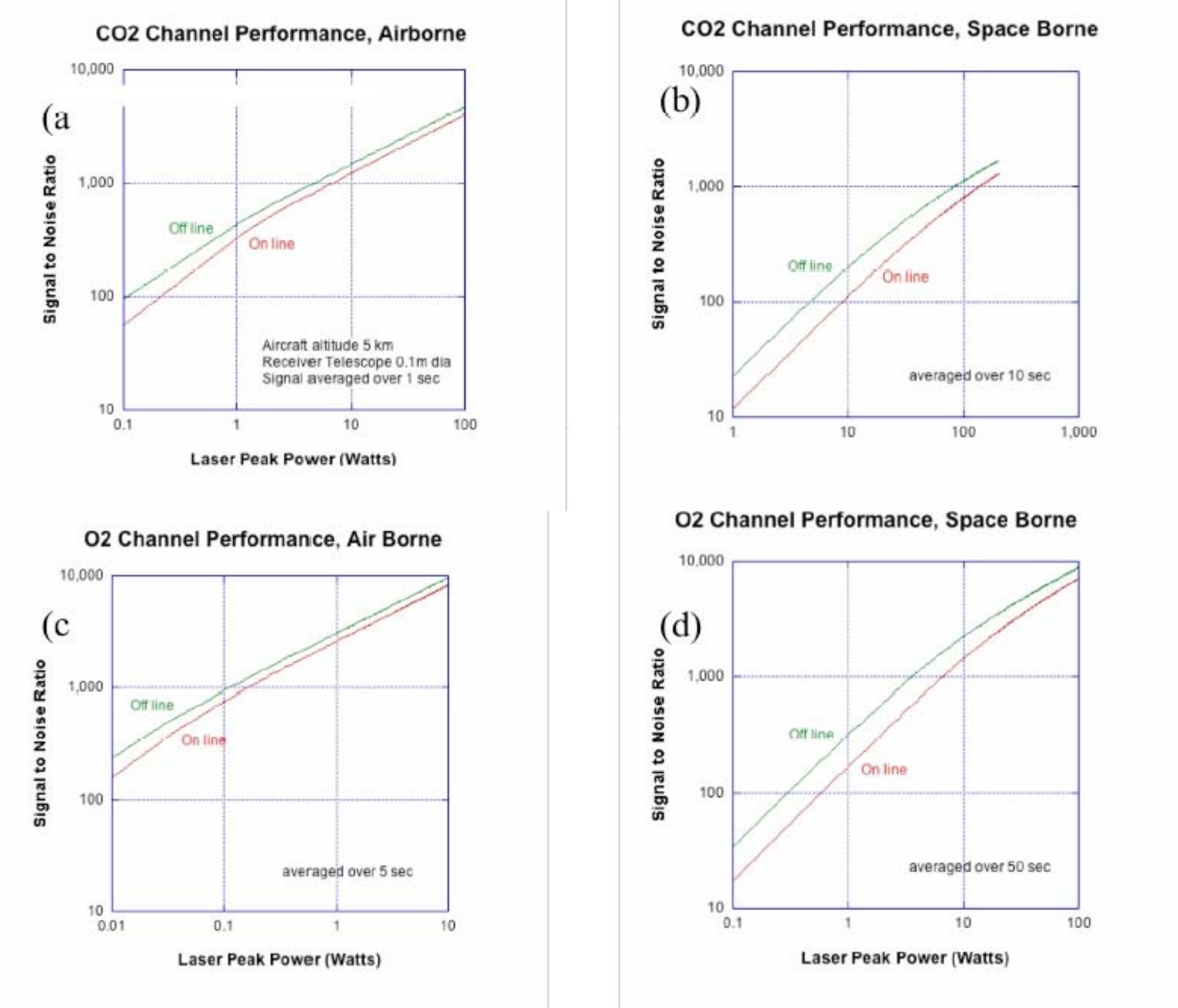
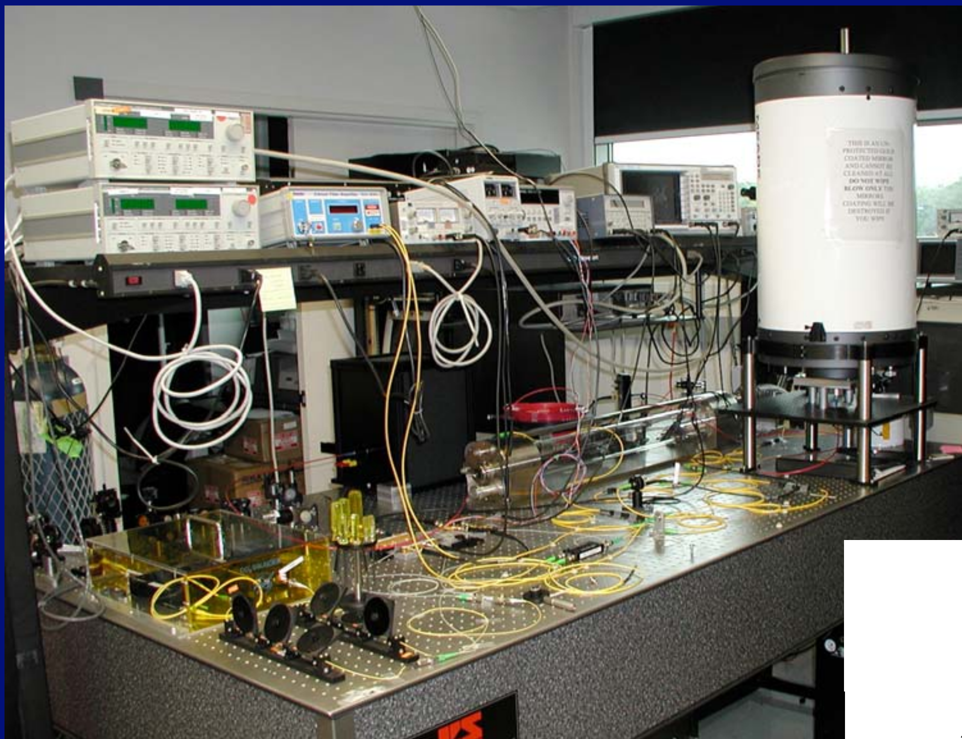


Figure 4. (a) CO_2 and O_2 seed laser modulation approach. (b) Schematic diagram for proposed spaceborne laser sounder. (c) Detail of the laser transmitter showing diode seed lasers and EDFA's.

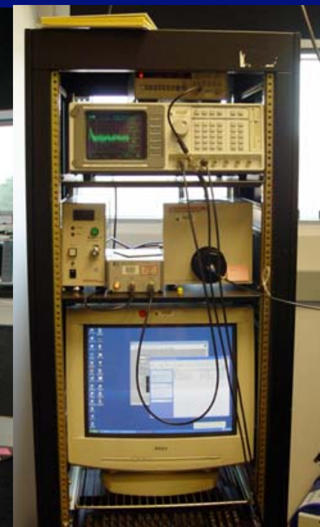
Performance Calculations for Airborne & Space Measurements



Ground-based CO_2 Profiling Lidar (Breadboard)



Profiling Lidar Breadboard

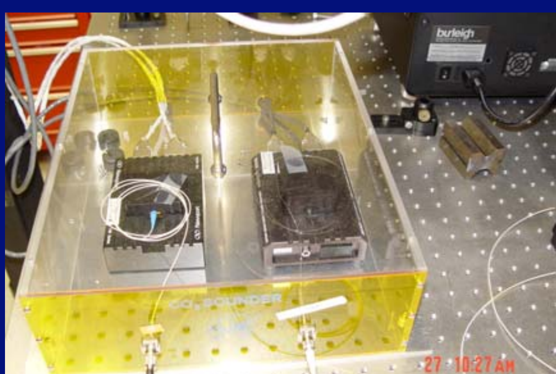


Detector & data acquisition system

Goal:

Measure CO_2 profiles to top of boundary layer to 1ppm hourly with 150m vertical resolution

(J. Burris, PI)

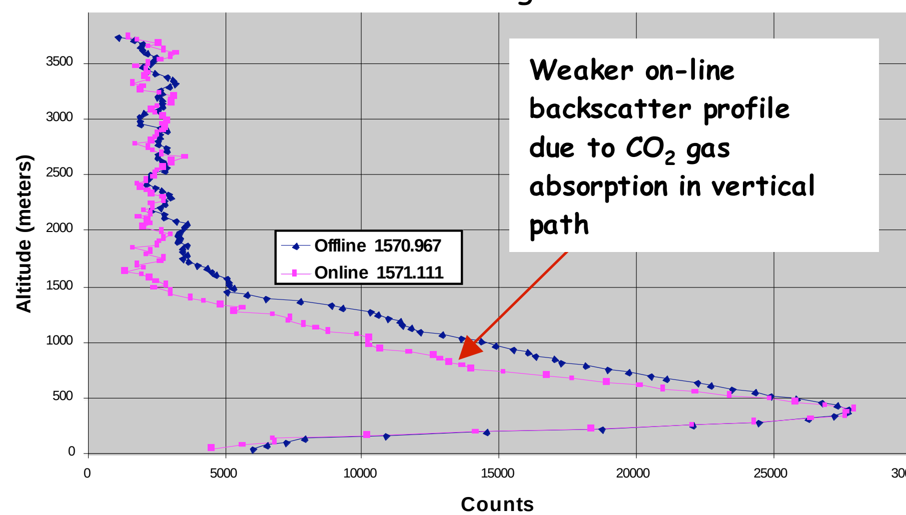


DFB seed Lasers

Example measurement:

Online & offline Profiles - 120 m vertical resolution

Six minute integration time



Milestones

1. Top-level Milestones			
Milestone #	**Months after task Start**	**Milestone Description**	**Status as of 5/15/06**
1	2	Complete specifying high stability fiber & fiber amp parts	**Done**
2	4	Initiate orbit simulation /CO2 assimilation flux recovery studies	**Done**
3	6	Improve breaboard photon counting resolution to 2000:1	Initiated
4	8	Demonstrate O2 measurements with seed lasers	**Done**
5	11	Initial Science modeling & mission trade study complete	Some planning
6	11	CO2 – demonstrate measurement stability over horizontal path	Prelim work on components
7	13	Start modifications for fielded breadboard version	
8	16	Evaluate fielded breadboard performance in laboratory test	
9	20	Measure CO2 at field site and compare with flux tower readings	some early site investigations
10	23	Intermediate science modeling & mission trade study complete	
11	24	Incorporate instr. modifications shown needed from field tests	
12	25	Demo O2 measurement over horiz path w/ photon counting	Sufficient O2 power for horiz path measurements
13	32	Complete reconfiguration and Initiate flight tests of airborne breadboard CO2 sounder	
14	35	Final Science modeling & mission trade study complete	
15	36	Data analyzed from flight test; start final report	

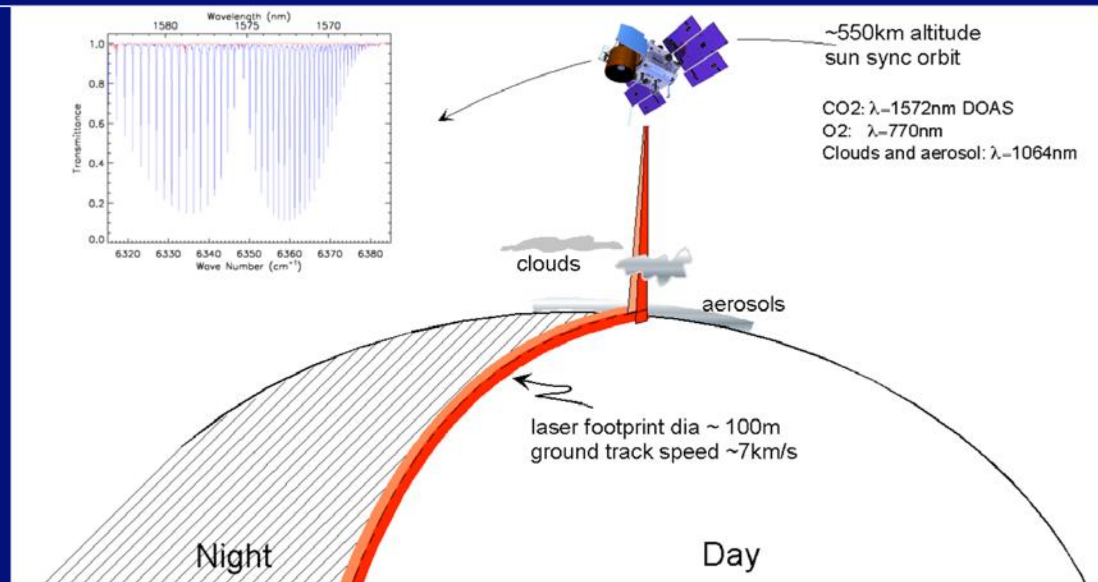
Summary

Why the laser sounder approach ?

- Measures:
  - at night & at all times of day
  - at high latitudes
  - through broken clouds
  - to cloud tops (& determines heights)
  - over oceans continuously
- Uses:
  - Common illumination & viewing path
  - Small (~100m) laser footprints
  - Strong echo signals from surface
  - Aerosol profiles to determine scattering in path
- Resolves 2-3 altitude layers

Why this technology ?

- Leverages B$'s by telecom. industry in laser technology
- Photon counting detector sensitivity
- Leverages knowledge from developing & operating ICESat & GLAS



Status:

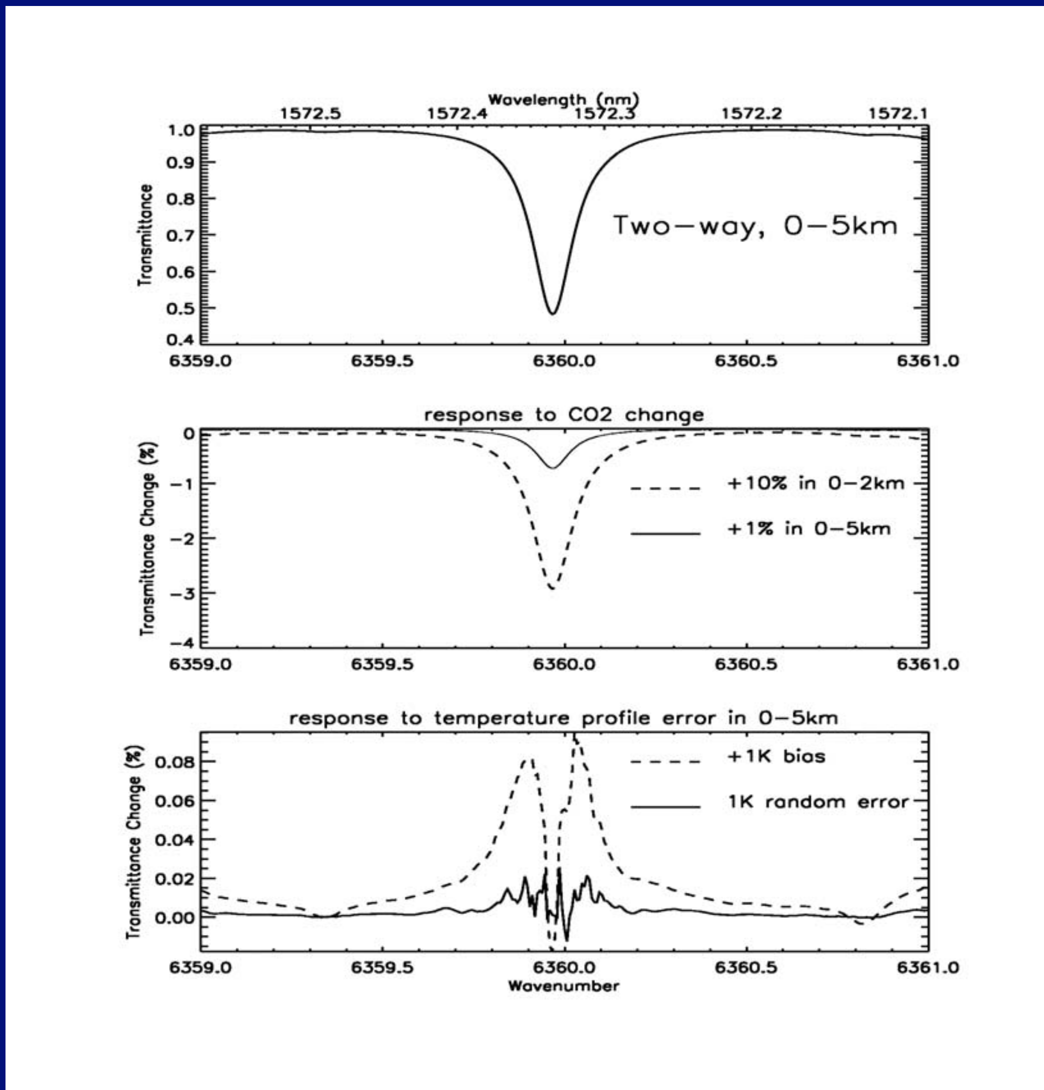
- Under development for ground-based & airborne demonstrations
- Ground-based CO2 profiling lidar being developed for in-situ measurements without aircraft or towers

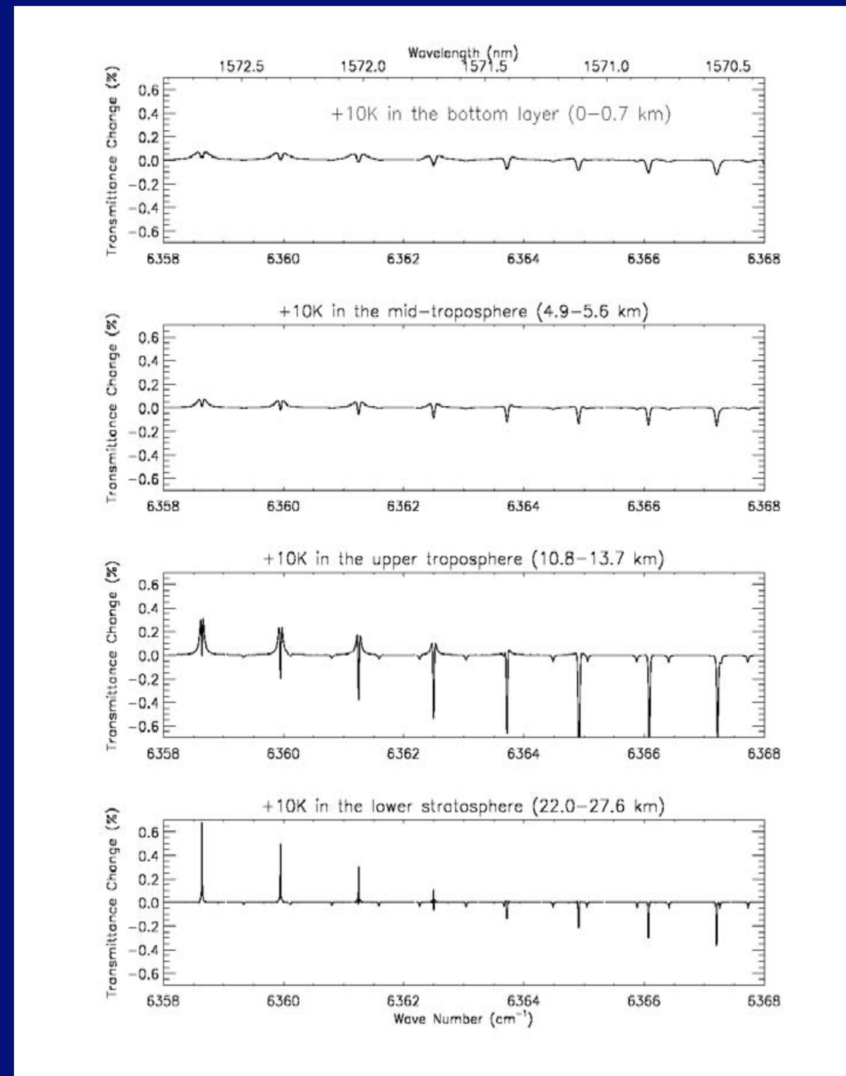
Next steps:

- Ground-based measurements at WLEF tower site (2007)
- Sounder space mission studies
- Sounder airborne (nadir viewing) demonstration (2008)
- Sounder space mission proposal

Backup

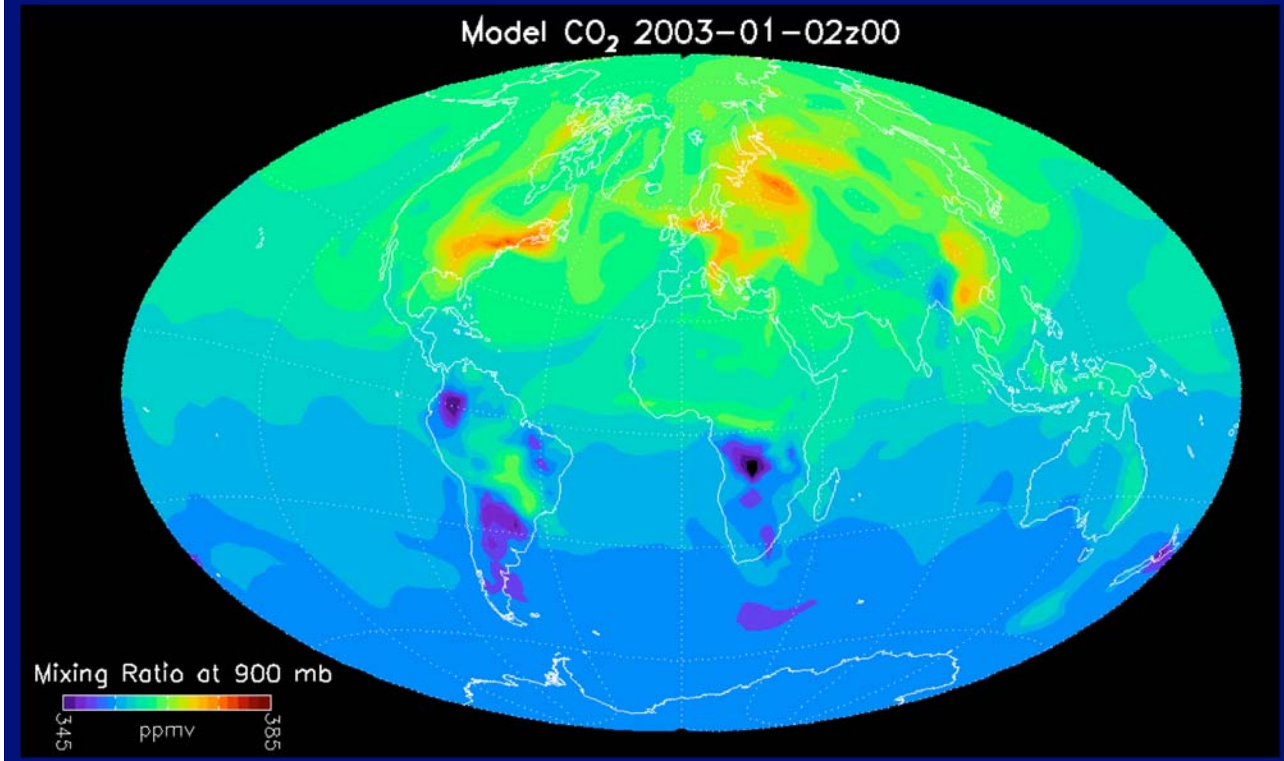
Example - CO_2 Line at 1572.33 nm & Temperature Sensitivity

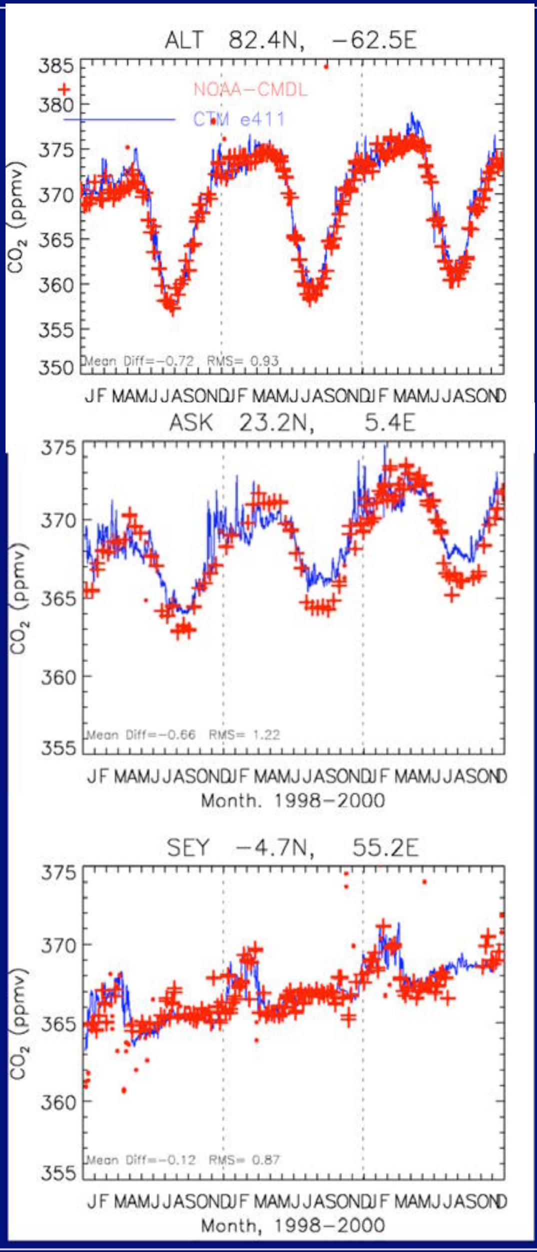




=> temperature profile data is required, but should be adequate

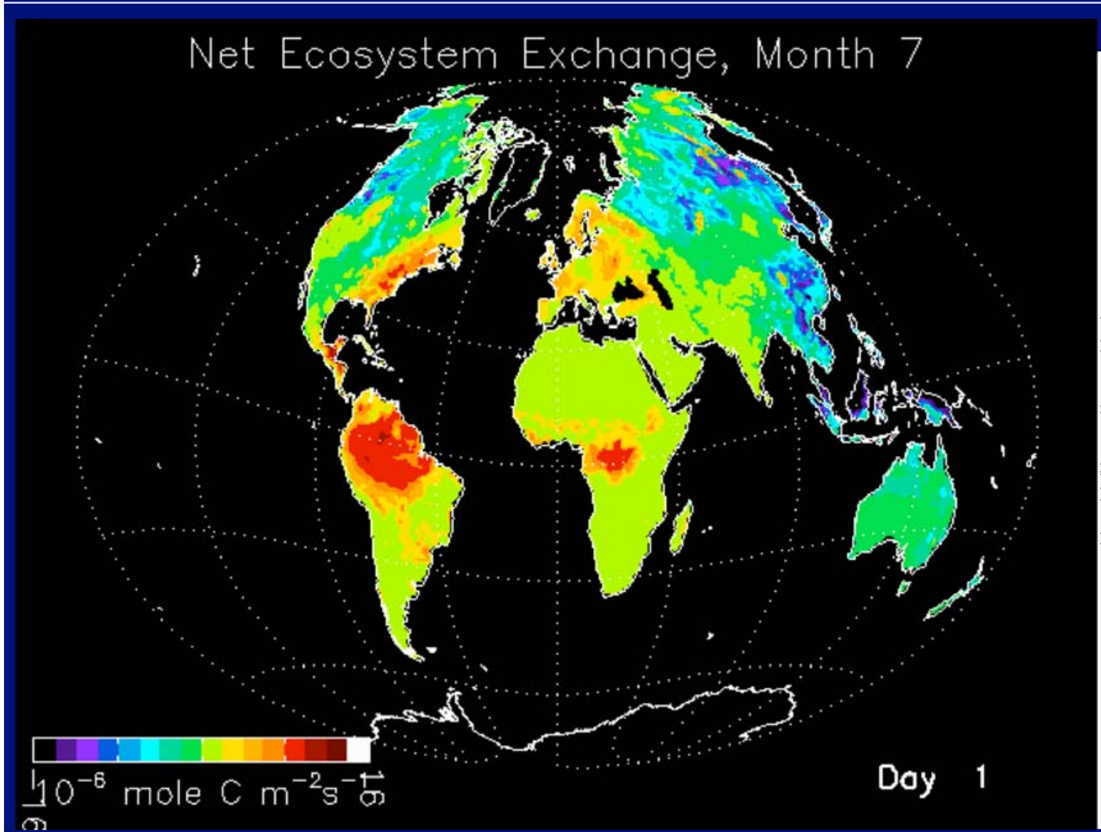
2. Simulating Atmospheric CO_2 Variability

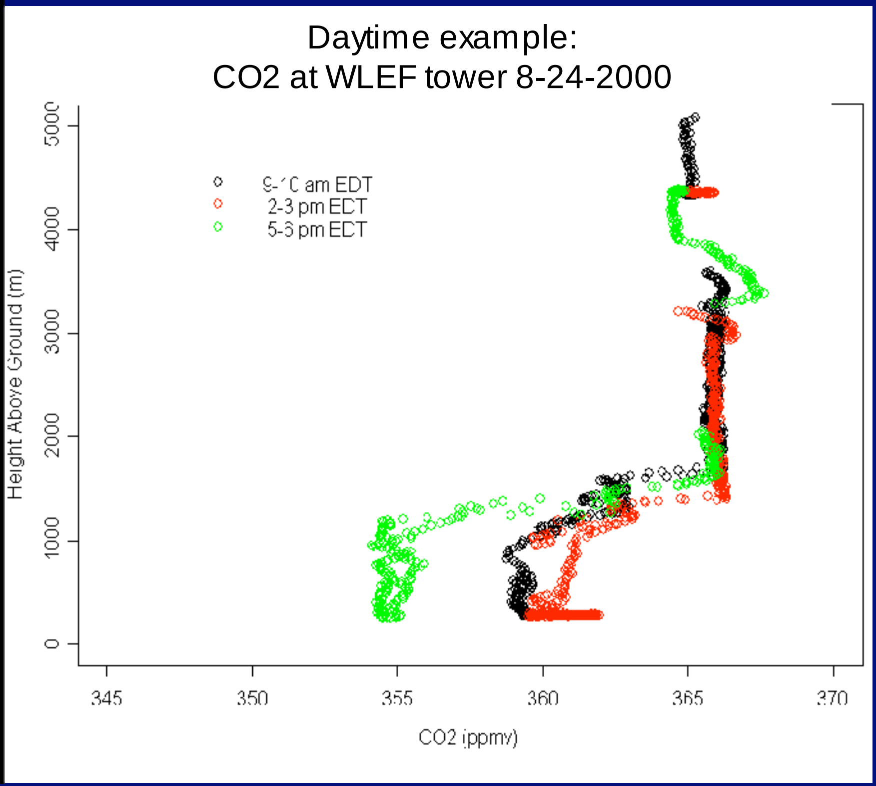




- CO_2 varies on a wide range of time and spatial scales
- Surface fluxes & atmospheric transport control CO_2 distribution
- Goal is to infer fluxes from atmospheric concentration measurements

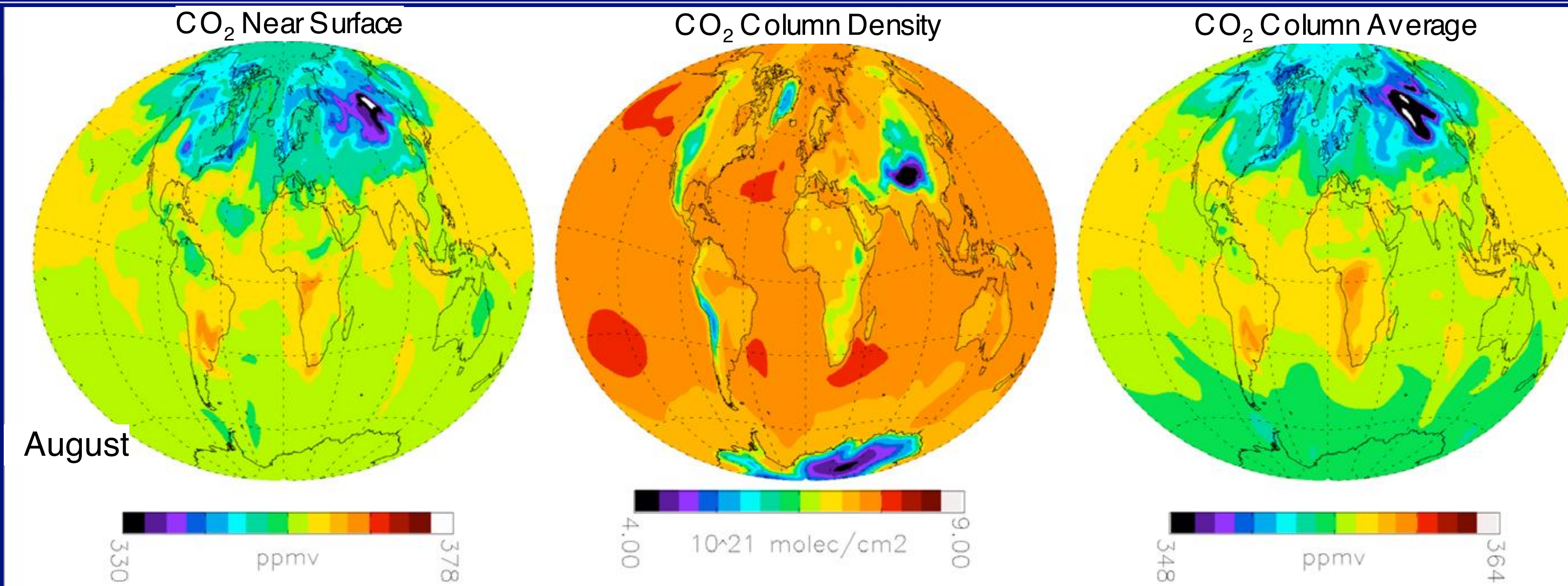
2. High-frequency CO_2 Changes

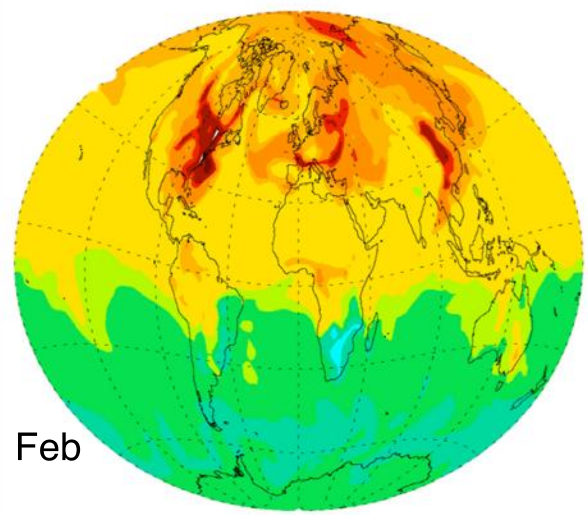




- Large changes occur in lower atmosphere
- Resolve scales to avoid bias

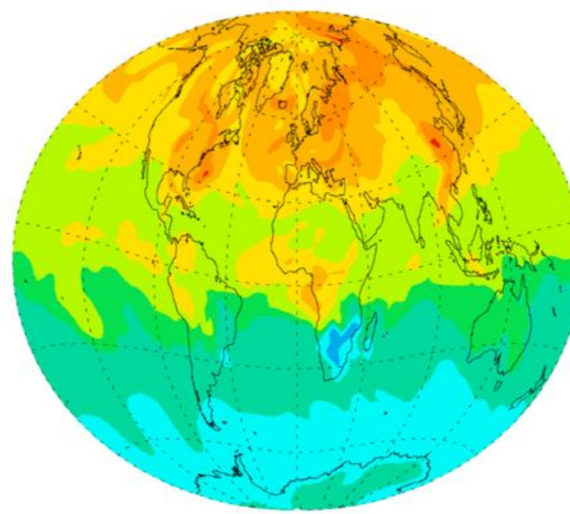
2. Column CO_2 Gradients



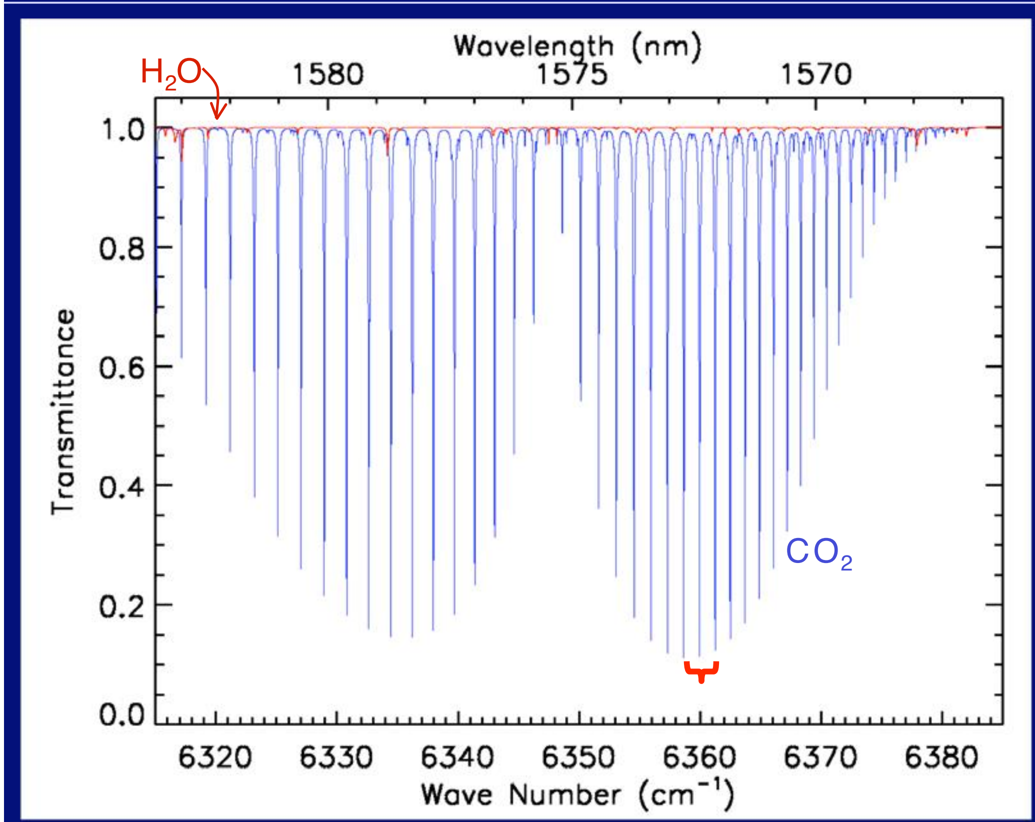


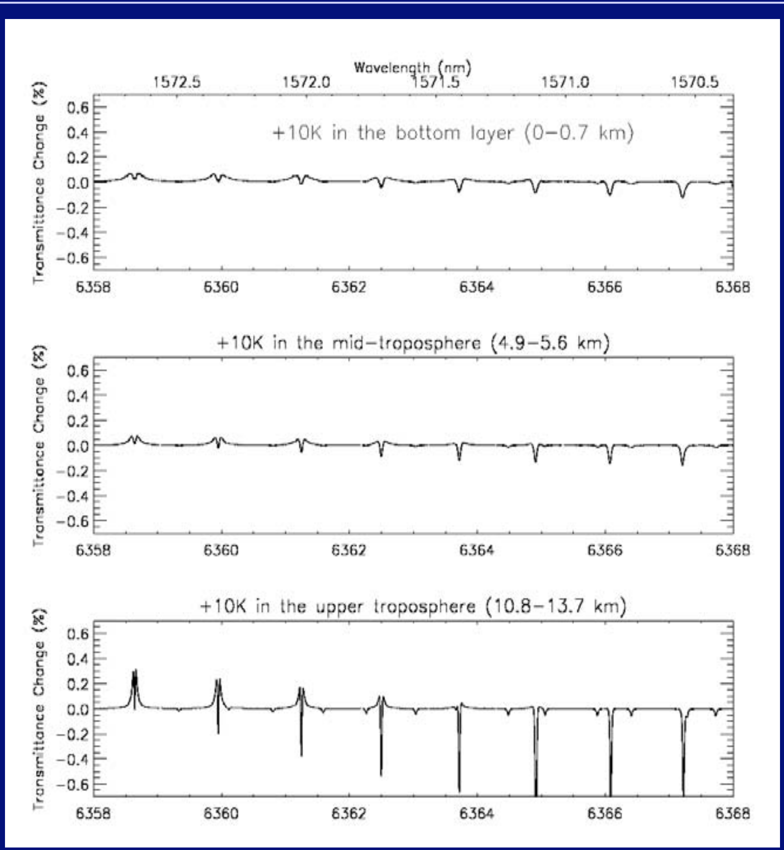
- Column density reflects changing surface height and pressure
  -path length normalization required: measure O_2

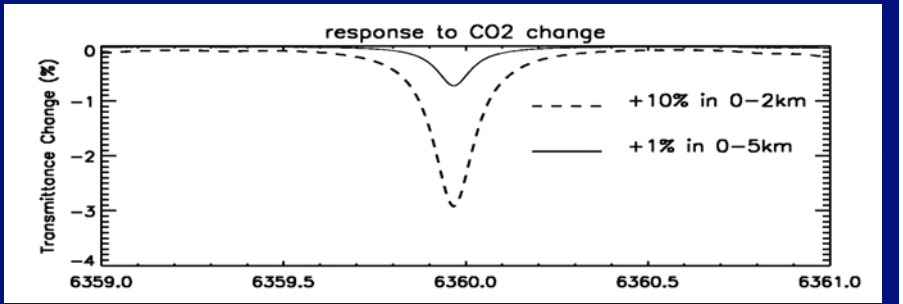
- Column CO_2 gradients are 2-3 ppmv/1000 km:
  <1% precision required



2. Modeling Atmospheric Spectral Transmission

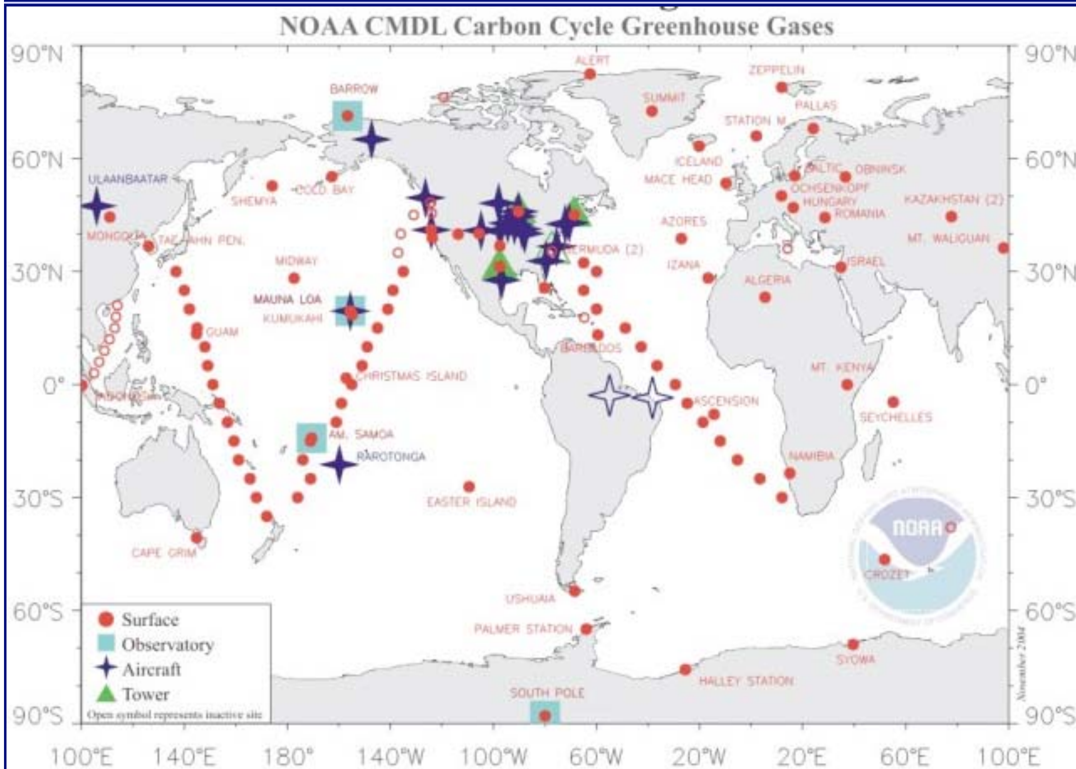




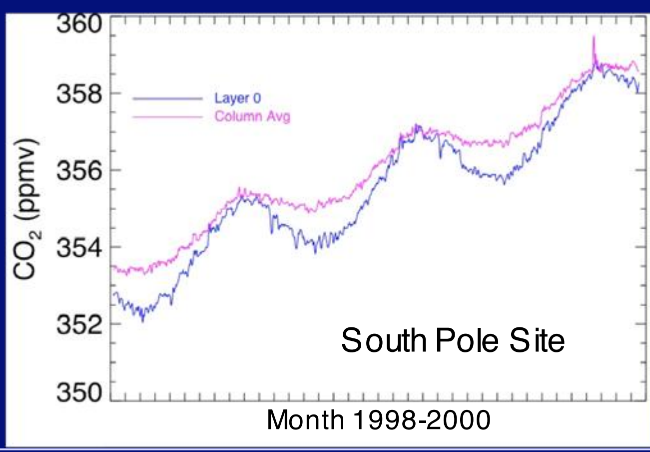


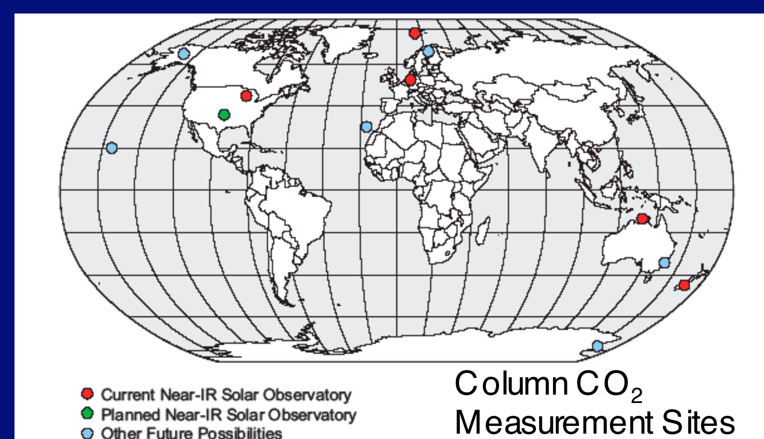
- Preferred spectral measurement region
  - good range of absorptivity
  - minimal temperature sensitivity
  - negligible interference from other species

2. Correlative Measurements



• Quantitative connection to ground-based CO_2 measurement record is crucial.





8. Related Conference Presentations

7. Instrument, Measurement and Technology Presentations:

"Laser Sounder for Measuring Atmospheric CO2 From Orbit" Michael A. Krainak, Arlyn E. Andrews, Graham Allan, John F. Burris, G. James Collatz, Haris Riris, Xiaoli Sun, Amelia Gates, James B. Abshire, 22nd International Laser Radar Conference Paper S2P-36 July 2004.

"Tunable solid-etalon filter for use in lidar receivers."Yakov Sidorin, David Lunt, Michael A. Krainak, and Mark A. Stephen. Earth Observing Systems IX, edited by William L. Barnes, James J. Butler, Proc. of SPIE Vol. 5542 133 October 2004.

"Laser Sounder for Global Measurement of CO2 Concentrations in the Lower Troposphere from Space: Progress" J. B. Abshire, **M. A. Krainak,** G.J. Collatz, X. Sun, H. Riris, A. Gates, J. F. Burris, EOS Trans. AGU, 85(47), Fall Meet. Suppl., Abstract SF43A-0783, San Francisco, CA, December 13-17, 2004.

"A CO2 Differential Absorption LIDAR System", A. M. Gates, J. F. Burris, A. E. Andrews, M. A. Krainak, H. Riris, X. Sun, J. B. Abshire, G. J. Collatz, S. Denning, L. Prihodko, M. Nicholls EOS Trans. AGU, 85(47), Fall Meet. Suppl., Abstract B23A-0923, San Francisco, CA, December 13-17, 2004.

"Small lidar for remote measurements from orbit of water-vapor, cloud, and aerosol profiles", Graham R. Allan, Michael A. Krainak, Amelia M. Gates, and James B. Abshire Proc. SPIE Int. Soc. Opt. Eng. 5653, 228 (2005)

"Photoionization of Trapped Carriers in Avalanche Photodiodes to Reduce Afterpulsing During Geiger-Mode Photon Counting" Michael A. Krainak CLEO May 2005

"Fiber lasers and amplifiers for science and exploration at NASA Goddard Space Flight Center" Michael A. Krainak, James Abshire, Graham R. Allan, Mark Stephen 18th Solid State and Diode Laser Technology Review Technical Digest, Directed Energy Professional Society paper Fiber-5, June 2005.

8. Related Conference Presentations

"Remote Sensing Of Atmospheric Carbon Dioxide And Methane Using Tunable Diode Lasers, Fiber Amplifiers And Photon Counting Detectors" Michael A. Krainak, James Abshire, Graham Allan, John Burris, G. James Collatz, Amelia Gates, Randy Kawa, Haris Riris, Xiaoli Sun , Tunable Diode Laser Spectroscopy Conference July 2005.

"Spectroscopic Remote Sensing Instrument For Orbital Atmospheric Pressure And Temperature Measurement" Mark Stephen, Michael Krainak, Michael Hayden, Tunable Diode Laser Spectroscopy Conference, July 2005

"A Ground Based Remote Sensing Tunable Diode Laser - Fiber Amplifier Instrument. Application To Carbon Dioxide Detection" Haris Riris, James Abshire, Graham Allan, John Burris, G. James Collatz, Amelia Gates, Randy Kawa, Michael A. Krainak, Xiaoli Sun, Tunable Diode Laser Spectroscopy Conference, July 2005.

"Near-infrared single-photon-counting detectors for laser instrument applications at NASA Goddard Space Flight Center" Michael A. Krainak, Xiaoli Sun and James B. Abshire, Single Photon Counting Workshop, October 2005.

"Laser Sounder for Global Measurement of CO2 Concentrations in the Troposphere from Space" Abshire, J. B.; Riris, H.; Krainak, M. A.; Sun, X.; Collatz, G. J.; Kawa, S. R.; Andrews, A.E." Session AS3.14, European Geosciences Union, April 2006.

"Methods to Improve Gain and Dark Current of Photon Counting Avalanche Photo-Diodes" Stewart Wu, Xiucheng Wu, Fow-Sen Choa, Michael A. Krainak; CLEO May 2006.

"A 1.57µm DIAL Lidar System for Range Resolved Measurements of Atmospheric CO2" Haris Riris, John Burris, Michael Krainak, Xiaoli Sun, James Abshire; CLEO May 2006

"A lidar for making range resolved CO2 measurements within the planetary boundary layer". John Burris, Haris Riris, Arlyn Andrews, Mike Krainak, Xiaoli Sun, Jim Abshire, Amelia Colarco, and William Heaps, 7th International Symposium on Tropospheric Profiling: Needs and Technologies (ISTP), June 2006.